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CHARACTERIZATION OF CONUS AND SAUDI ARABIAN FINE-GRAINED SOIL SAMPLES

INTERIM REPORT
BFLRF No. 294

By

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Soil samples were collected from various geographical areas in the United States and Saudi Arabia. The samples were obtained from U.S. military installations where off-road maneuvers are conducted. Saudi Arabian samples were obtained from the deserts surrounding Riyadh. The soil samples were characterized using particle size distributions, elemental analysis, mineral composition, and particle angularity. Particle size distributions were also determined for a simulated fuel cell during intermittent and continuous mixing conditions. The results obtained from the worldwide soil sampling were compared against AC and PTI test dusts.

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18. SUBJECT TERMS

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EXECUTIVE SUMMARY

__Problems and Objectives__: The previous manufacturer of test dust used in fuel filtration evaluations has ceased production of the standard test dust. The lack of this standard dust has disrupted fuel, oil, and air filtration testing. Although another manufacturer has begun production of similar test dusts, the new test dusts are different enough to prevent comparison with the test data derived from use of the previous test dust. The objective of this program was to characterize various fine-grain soil samples collected from the continental United States (CONUS) and from Saudi Arabia to determine if the test dust specification requires modification to ensure that the test dust composition resembles naturally occurring soils in significant aspects.

__Importance of Project__: Fuel filtration requirements are changing due to new engine designs that require higher injection pressures and lower emission standards. Test dusts for evaluating these filters have changed, and there is a need for filtration testing standardization among government and industry.

__Technical Approach__: Soil samples were obtained from various CONUS military installations at which wheeled and tracked vehicles operate. Samples were also retrieved from the deserts in Saudi Arabia during Operation Desert Shield/Storm. Particle size distribution, elemental analysis, mineral composition, and particle angularity were determined. These results were then compared with characteristics of reference test dust materials.

__Accomplishments__: Soil samples from CONUS and Saudi Arabia were compared to standard filtration test dusts. This comparison revealed that the standard test dusts failed to agree with the particle size distribution or composition of the sands sampled in this limited survey.

__Military Impact__: The samples obtained for the study were collected at off-road sites where heavy equipment, i.e., tanks, armored personnel carriers, refueling tankers, etc., travel. These samples give an initial view of the sand and dust that military and off-road vehicle filtration systems encounter in this type of environment. From this investigation, filtration design and selection can be performed more intelligently.

FOREWORD/ACKNOWLEDGMENTS

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I. INTRODUCTION

New engine designs, higher injection pressures, and more stringent emissions requirements are changing the fuel system filtration requirements for today's vehicles. The fuel filtration system must remove particles and water from the fuel for the engine to remain in good condition. This report focuses on the particulate aspects of fuel filtration. Particle size distributions, elemental analysis, infrared spectra, and particle angularities are determined for various soils obtained from military bases in the continental United States (CONUS) and from Saudi Arabia during Operation Desert Shield/Storm. With the fluctuating parameters ongoing in the filtration industry, it was felt that this would be an opportune time to reevaluate the industry's test dust requirements. From this information, the filtration industry should obtain a better understanding of the filtration requirements and test dust needed to properly evaluate new filters.

II. BACKGROUND

The U.S. Army encountered numerous fuel system and engine problems during Operation Desert Shield/Storm.(1)* Many of these problems were caused by ingestion of soil into these systems. Inspection of fuel pumps on the High-Mobility Multipurpose Wheeled Vehicle (HMMWV) and Commercial Utility Cargo Vehicle (CUCV) revealed gross quantities of soil. As shown in Fig. 1, the HMMWV filter has excellent efficiency when tested under laboratory conditions. However, when the test conditions are designed to simulate real-life conditions, i.e., vibration and start/stop cycles, Fig. 2 illustrates why the fuel pumps were full of soil. Work performed by Onion and others has shown that the most damaging particles range in size from 5 to 20 micrometers and that less than 5 grams of abrasive of the size and composition found in many vehicle fuel systems can wear out an injection pump.(2)

Obviously, these filters failed to protect the military equipment as expected. In response to this lack of protection, the question arose, "How are military fuel filters qualified?" An investigation into the filtration requirements for military vehicles revealed that no military specification for

* Underscored number in parentheses refers to references at the end of this report.

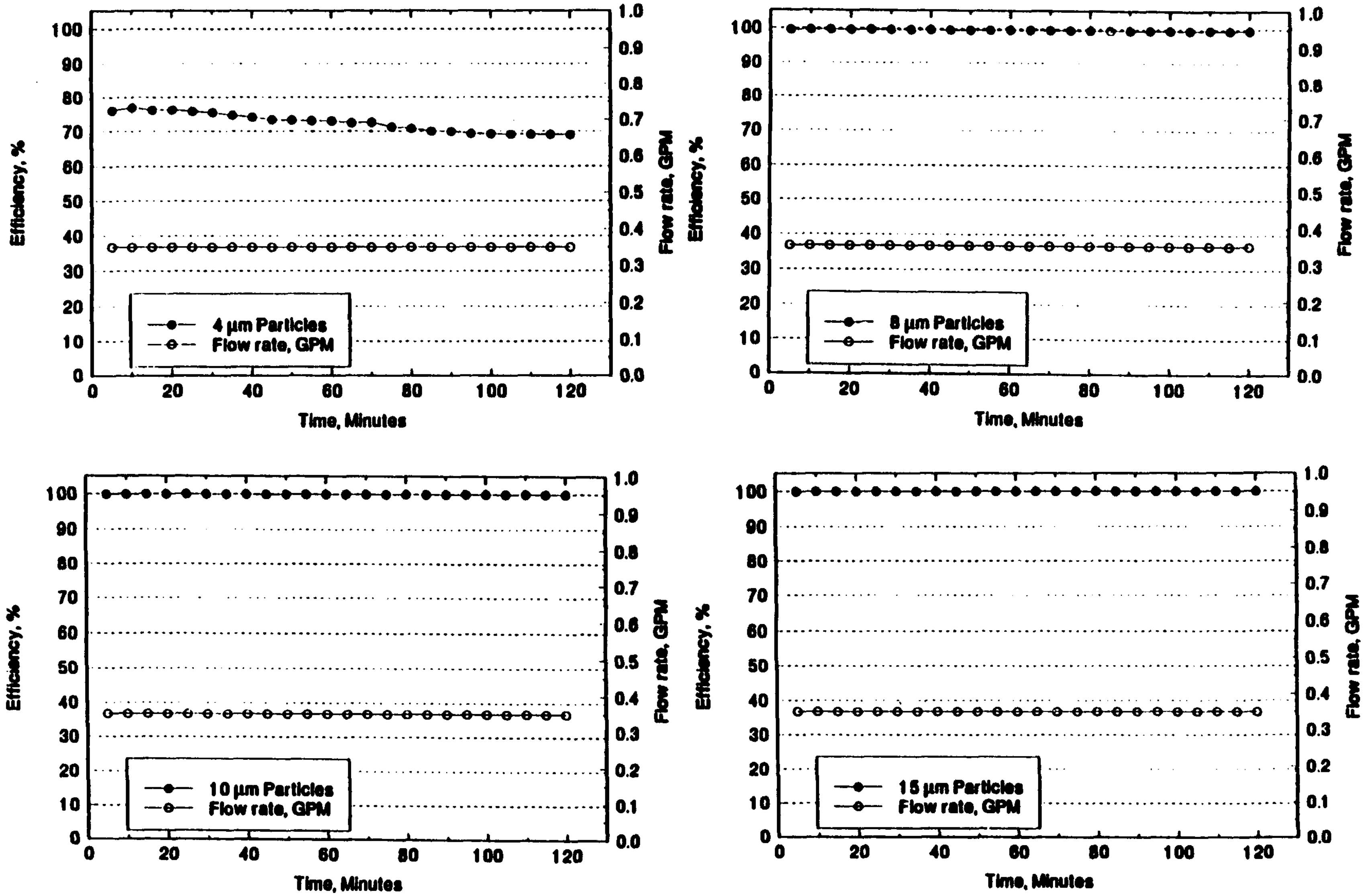

Figure 1. <u>Filter data for HMMWV filter with constant flow and PTI SAE fine test dust</u>

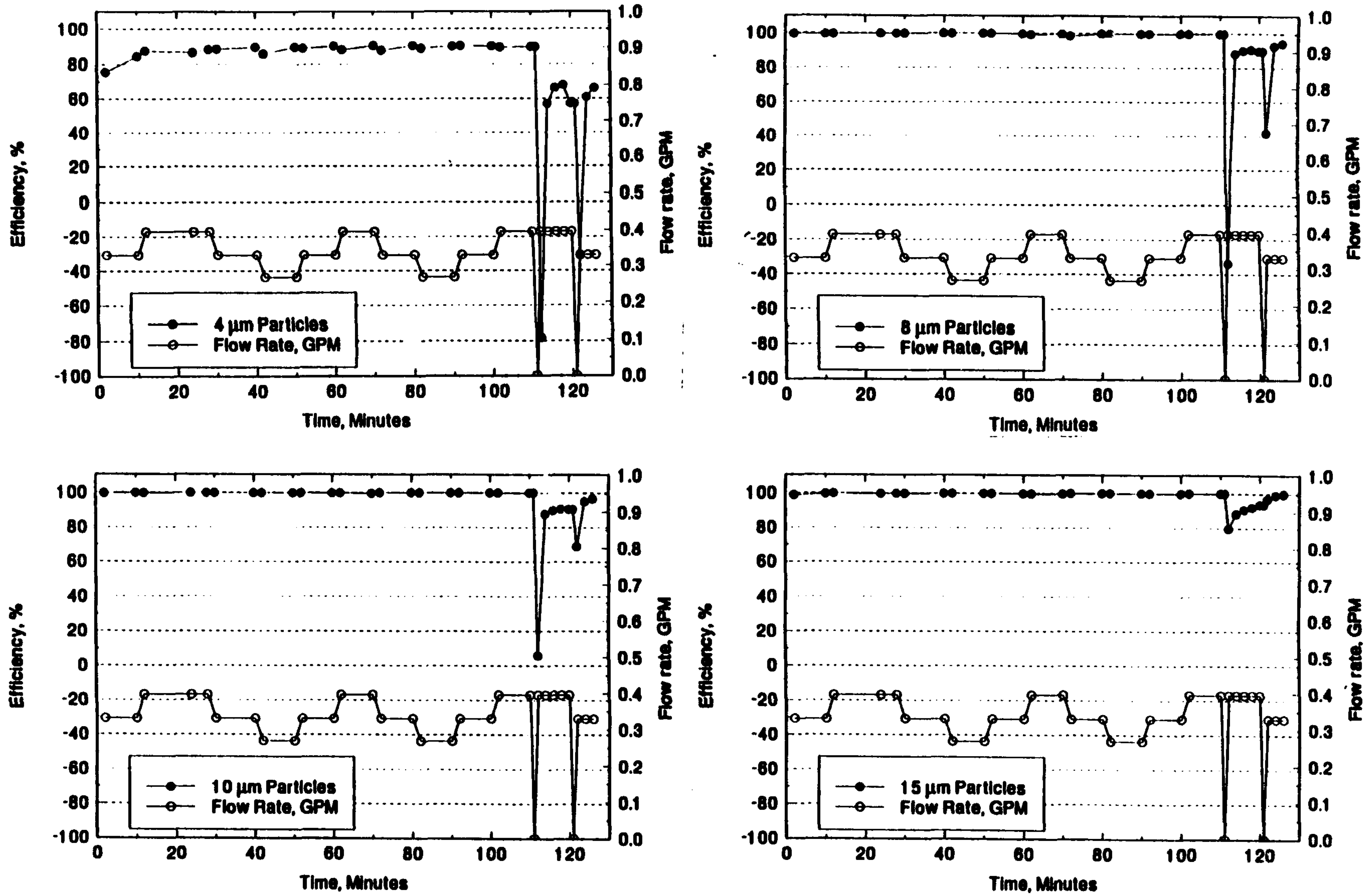

Figure 2. <u>Filter data for HMMWV filter with graded flow and PTI SAE fine test dust</u>

qualifying fuel filters for vehicle use currently exists. The standard practice for filter selection has been to use filters similar to those in the military inventory or the filter supplied by the engine manufacturer. However, each engine and filter manufacturer has its own method for qualifying fuel filters. Therefore, varying degrees of quality are produced. The lack of a standardized test method and procedure occurs both in the United States and in the European community.(3)

To complicate these issues, the only previous producer (AC Rochester) of test dust is no longer producing test dust. Although another manufacturer (Powder Technology, Inc.) is now producing filter test dust, the new test dust does not have the same particle size distribution as the test dust previously produced.

III. APPROACH

Representatives at various CONUS military installations were contacted to obtain off-road soil samples from those areas in which wheeled and tracked vehicles operated. Also, five additional samples were obtained from Saudi Arabia during Operation Desert Shield/Storm. The military bases and locations are shown in TABLE 1 and Fig. 3, respectively. The installation number in TABLE 1 corresponds to the number in Fig. 3.

TABLE 1. Participating Military Installations

Installation No.	Installation	No. of Samples
1	Fort Bliss, TX	1
2	Fort Hood, TX	1
3	Fort Stewart, GA	5
4	Fort Polk, LA	1
5	Fort McClellan, AL	1
6	Yuma Proving Ground, AZ	1
7	Fort Irwin, CA	1
8	Camp Pendleton, CA	1
9	Twentynine Palms, CA	1

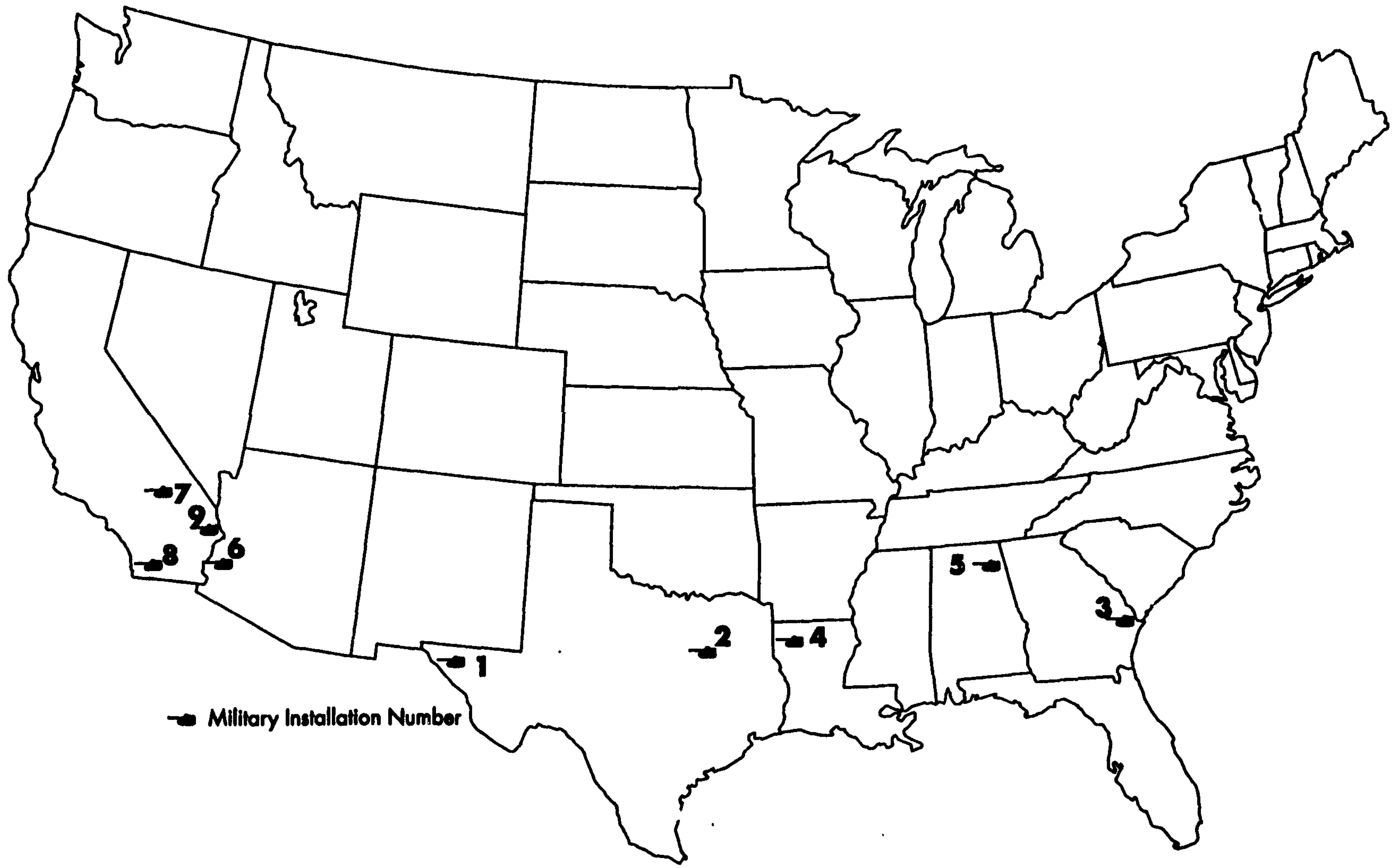

Figure 3. Military base locations

AC Fine and Coarse Test Dust and PTI Fine and Coarse Test Dust were analyzed for reference and comparison. In addition, airborne dust was sampled from 0.9 to 3 meters (3 to 10 feet) at 0.3-meter (1-foot) increments at Camp Pendleton, CA.

IV. PROCEDURES AND RESULTS

The soil analyses included: 1) particle size distribution, 2) elemental analysis by X-ray fluorescence, 3) mineral characterization by infrared spectroscopy, and 4) size and angularity characterization using a Scanning Electron Microscope (SEM).

A. Particle Size Distribution

The particle size distribution was determined using an on-line particle analyzer. The system used for this analysis contains two sensors and counters and is commonly used for filter efficiency testing, which requires simultaneous sampling upstream and downstream of the test filter. The dual-sensor counter simultaneously controls both light-blocking laser diode sensors.

1. Distribution Determination

The test fluid used for these analyses was Viscor L4264V91 fluid. The test fluid was first prefiltered through a 2-micrometer cleanup filter until the fluid contained less than 10 counts/milliliter at 10 micrometers. Since the dust samples were obtained from the natural environment, many of the samples contained stones, sticks, and other debris. In order to remove this debris, all samples were passed through a No. 200 mesh sieve.

As defined by the American Society for Testing and Materials (ASTM) D 2487-90, "Standard Test Method for Classification of Soils for Engineering Purposes, " soils which pass a No. 200 (75 micrometer) U.S. standard sieve are classified as fine-grain soils. This fine-grain soil consists of silts and clays. Sands are defined as particles of rocks that will pass a No. 4 (4.75 mm) sieve and be retained on a No. 200 sieve. Silts are nonplastic or very slightly plastic and exhibit little

or no strength when air dry. Silts will cause abrasive wear in a vehicle system. Clays can be made to exhibit plasticity within a range of water contents and exhibit considerable strength when air dry. Clays will tend to plug filters due to its tendency to agglomerate.(4) The collected soil samples are technically "sands," but since this survey is only interested in the samples which pass a No. 200 sieve, the samples will be referred to as fine-grain soils or soils.

A weighed amount of soil was placed into a small container of measured test fluid, sonicated for 2 minutes, and then placed into a known volume of clean test fluid in the test stand (Fig. 4). The contaminated test fluid was circulated through the test stand for approximately 10 minutes to allow the system to equilibrate. The particle size distribution was measured for 1-minute intervals, every other minute, for ten measurements. This procedure was repeated three times, each time after the test fluid was cleaned and treated with fresh soil samples.

The results of the tests, ranging from 4 to 20 micrometers in size, were averaged and reported in counts per mL based on one milligram of test dust per liter of test fluid, as per ISO 4402,

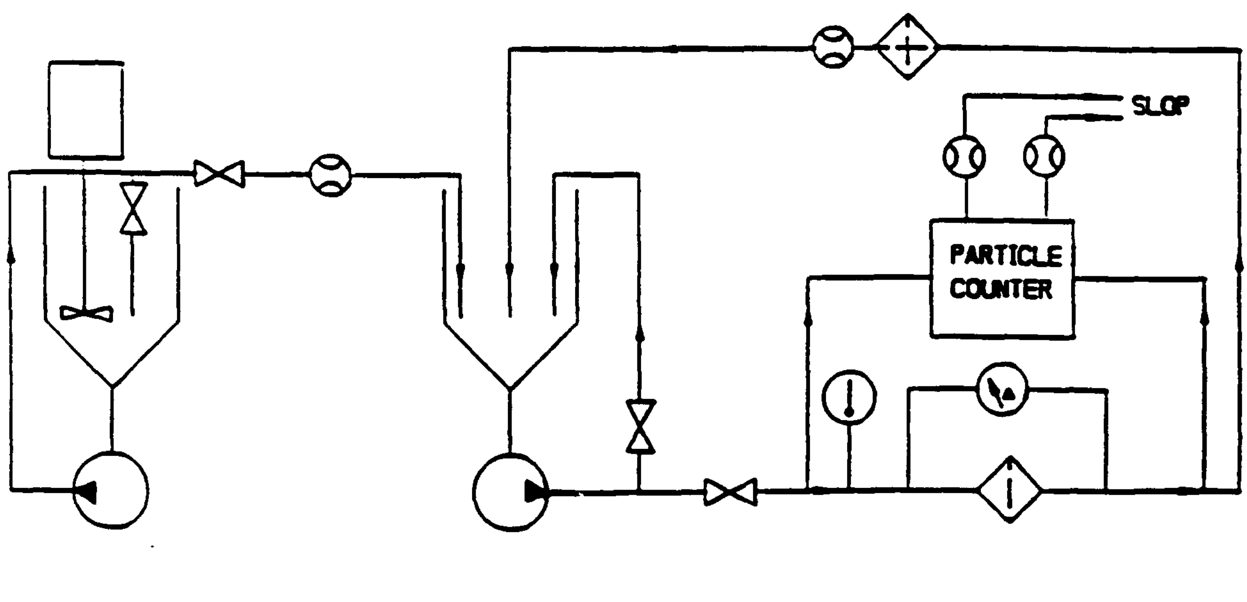

Figure 4. Filter efficiency test stand

"Hydraulic Fluid Power-Calibration of Automatic-Count Instruments for Particles Suspended in Liquids-Method Using Classified AC Fine Test Dust Contaminant." The particle size distributions are shown in TABLE 2.

The generated AC Fine Test Dust (ACFTD) distribution was compared to the ISO 4402 specification to confirm validation of the particle counter.

TABLE 2. Particle Size Distribution of Soil Samples

Sample No.*	Location	Particle Size, micrometers								
		4	5	6	7	8	9	10	15	20
1	Ft. McClellan, AL	1,020	823	694	552	414	317	247	83.6	36.0
2	Twentynine Palms, CA Fuel Debris	1,014	588	423	294	203	152	120	53.7	33.4
3	PTI Fine Test Dust	1,002	707	557	421	294	210	163	58.7	30.2
4	AC Fine Test Dust	751	579	467	357	262	199	156	56.0	25.4
5	Ft. Stewart, GA Fuel Debris	705	497	430	348	278	230	196	107	62.2
6	Saudi Arabia 5	609	399	323	254	197	161	135	71.2	44.8
7	Saudi Arabia 1	581	426	343	265	200	159	130	57.2	30.3
8	Ft. Polk, LA	567	418	343	271	208	165	136	59.4	31.6
9	Yuma Proving Ground, AZ	561	364	280	206	148	117	90.0	37.5	20.7
10	Saudi Arabia 2	560	426	359	289	227	183	153	67.2	34.3
11	Ft. Hood, TX	517	377	309	243	186	149	123	57.6	32.1
12	AC Coarse Test Dust	504	353	283	218	164	128	103	41.4	20.3
13	PTI Coarse Test Dust	491	354	285	222	167	127	105	40.7	20.8
14	Ft. Stewart, GA Red Cloud	337	278	237	195	156	128	107	48.3	25.6
15	Ft. Irwin, CA	332	231	184	143	110	89.0	74.2	35.4	19.6
16	Camp Pendleton, CA	330	222	178	139	107	87.9	74.2	47.3	23.0
17	Ft. Stewart, GA M1A1 Air Filter Debris	325	250	218	185	155	132	115	62.0	36.7
18	Saudi Arabia 4	325	250	218	185	155	132	115	62.0	36.7
19	Ft. Bliss, TX	239	132	100	74.5	57.2	43.7	35.8	16.5	9.8
20	Saudi Arabia 3	233	141	111	83.9	65.3	53.5	44.7	23.7	15.2
21	Ft. Stewart, GA	176	135	113	93.3	76.7	64.4	55.3	27.4	15.5
22	Ft. Stewart, GA Range 18553	154	116	97.0	78.0	62.5	52.6	45.4	25.0	13.7

* The sample number designates each sample in subsequent tables.

2. Airborne Soil Sampling

A 3-meter (10-foot) pole with sampling containers was placed next to a dirt road traversed by U.S. Marine Corp Light Armored Vehicles (LAVs). The sampling containers were placed on the pole 0.9 meter (3 feet) from the bottom and at 0.3-meter (1-foot) intervals. Samples were collected, SEM micrographs were taken (Figs. 5 and 6), and particle size distributions were determined (TABLE 3).

The samples taken from the 3-meter (10-foot) container consisted of dust, leaves, sticks, and insects. The weight percentage, as a function of height, of the total dust samples collected are shown in TABLE 4.

The increase in mass at 1.5 meters (5 feet) is assumed to be a result of the air currents generated by the vehicles. This irregularity in the data agrees with the 1.5-meter (5-foot) particle size

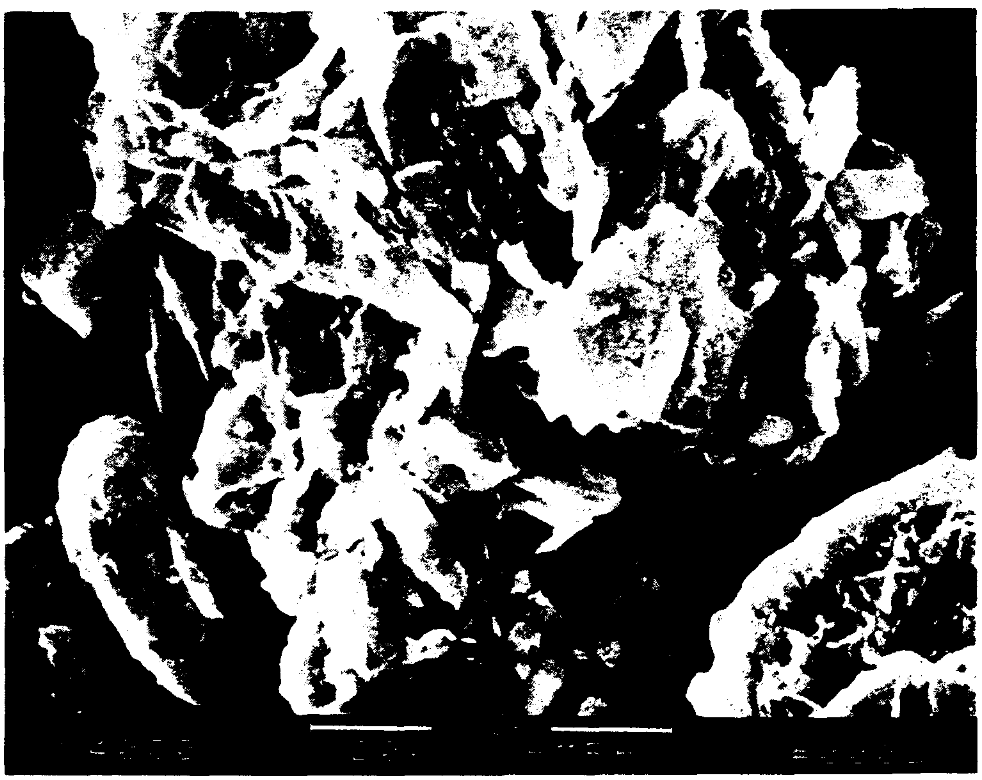

Figure 5. Airborne soil sample, Camp Pendleton, CA

Figure 6. Airborne soil sample, Camp Pendleton, CA

TABLE 3. Particle Size Distribution as a Function of Height

Meters (feet)	Particle Size, micrometers								
	4	5	6	7	8	9	10	15	20
0.0 (0)	330	222	178	139	107	87.9	74.2	47.3	23.0
0.9 (3)	435	278	222	173	134	109	92.5	48.9	29.9
1.2 (4)	434	285	229	179	140	115	97.1	51.9	31.8
1.5 (5)	493	322	257	199	153	124	103	52	30.6
1.8 (6)	498	329	264	206	159	128	107	54.4	32.7
2.1* (7)	476	307	246	191	148	121	101	53.6	32.6
2.4* (8)	491	318	253	197	152	124	104	55.1	33.6
2.7* (9)	514	348	280	217	166	134	112	55.6	32.8
3.0 (10)	--†	--†	--†	--†	--†	--†	--†	--†	--†

* Only enough sample for one particle size distribution determination.
† Insufficient sample to perform a particle size distribution.

TABLE 4. Weight Percentages of Total Airborne Dust Taken From Camp Pendleton, CA

Height, m (ft)	Percentage, wt%
0.9 (3)	20.8
1.2 (4)	14.5
1.5 (5)	18.4
1.8 (6)	13.5
2.1 (7)	10.7
2.4 (8)	9.4
2.7 (9)	9.7
3.0 (10)	3.0

distribution in TABLE 3. It should be noted that the body of the LAV also stands approximately 1.5 meters (5 ft) from the ground. Figs. 5 and 6 illustrate some of the unique shapes and angularities found in fresh fractures. These fractures appear to be caused by a crushing action.

B. Elemental Analysis

The typical chemical composition of the AC Fine Test Dust (ACFTD) is shown in TABLE 5.(5) Compositions of the soil samples collected in this study were determined using a Kevex Model 770 energy-dispersive X-ray fluorescence analyzer with a Quantum thin-film detector window. Each sample was prepared as a loose powder in a disposable sample cup with a prolene film, and standard comparisons were based on elemental oxides. The elemental compositions and oxide weight comparisons of the samples collected are shown in TABLES 6 and 7, respectively.

Common mineral compositions may be expressed in oxide weight percents. Quartz, for example, is 100 percent SiO_2. Talc would be described as 63.5 percent SiO_2 and 31.7 percent MgO, with the remainder being water. Calcite or aragonite would be 56 percent CaO and 44 percent CO_2, and kaolinite clay would be 46.5 percent SiO_2, 39.5 percent Al_2O_3, and the remainder water.

TABLE 5. Chemical Analysis of Typical AC Fine Test Dust

Component	wt%
SiO_2	65 to 76
Al_2O_3	11 to 17
Fe_2O_3	2.5 to 5.0
Na_2O	2 to 4
CaO	3 to 6
MgO	0.5 to 1.5
TiO_2	0.5 to 1.0
V_2O_3	0.10
ZrO	0.10
BaO	0.10
Loss on Ignition	2 to 4

The AC Fine Test Dust would consist of a blend of quartz and clay minerals, using these compositions. It would contain little or no calcium- or magnesium-containing minerals. Mineral compositions of the sands collected at the various locations are discussed in the captions of the microphotographs of the samples.

C. Mineral Characterization

1. Infrared Spectroscopy

Mineral types included in the soils observed include clays, quartz, calcium carbonate, and talc. Figs. 7 through 13 include reference spectra for the pure materials and spectra obtained from size segregated samples of soils from test locations. All soil sample infrared spectra are found in Appendix A. Infrared spectra were obtained by depositing fine particle portions of samples suspended in chloroform onto a horizontal attenuated total reflectance (ATR) cell on a Fourier Transform Infrared (FTIR) spectrophotometer. The deposit was allowed to dry completely, then analysis was performed.(6) Absorbances were compared with reference spectra of minerals.

TABLE 6. Elemental Composition of Soil Samples, wt%

Sample No.	Al	Si	S	Mg	Cl	K	Ca	Ti	Fe	Zn	Pb	Sr	Zr	Ba	Cd
1	10.5	23.2	0.1	--*	--	0.2	2.0	0.3	3.4	--	--	--	--	--	--
2	--	0.8	8.3	--	2.6	--	7.1	0.5	2.1	12.3	1.4	--	--	--	--
3	10.2	30.8	--	--	--	3.6	4.2	1.0	9.6	--	--	0.5	0.6	0.8	--
4	12.7	28.9	--	--	--	1.5	1.3	0.3	3.0	--	--	0.2	0.2	0.4	--
5	--	43.5	0.1	--	--	0.2	0.3	0.1	3.6	0.9	0.6	--	--	--	--
6	1.8	11.2	1.1	27.6	0.4	0.1	6.9	--	0.4	--	--	0.1	0.2	0.2	--
7	3.9	13.8	--	--	--	0.5	8.0	0.7	3.1	--	--	0.1	0.9	--	--
8	9.8	16.4	0.2	--	--	0.2	5.4	0.3	2.4	--	--	0.2	0.7	--	--
9	10.5	17.2	--	7.0	--	1.0	3.5	0.3	3.4	--	--	0.1	0.2	0.1	--
10	2.8	6.3	--	--	--	0.2	10.6	0.1	1.1	--	--	0.1	0.1	--	--
11	5.0	9.5	0.2	--	--	0.2	8.2	0.1	0.9	--	--	0.1	0.1	--	--
12	10.1	31.0	--	--	--	3.7	2.8	0.3	2.8	--	--	0.1	0.2	0.7	--
13	5.9	25.8	--	--	--	1.5	1.9	0.3	3.1	--	--	0.1	0.1	0.3	--
14	10.0	33.5	--	--	--	--	--	0.5	1.0	--	--	--	0.9	--	--
15	11.4	21.2	--	--	--	1.1	2.0	0.3	3.3	--	--	0.2	0.2	0.4	--
16	7.0	19.4	--	--	--	1.3	5.2	0.9	11.8	--	--	0.3	0.4	0.4	--
17	14.1	27.5	--	--	--	0.1	0.1	0.6	2.4	--	--	--	0.9	--	--
18	6.8	12.6	1.3	10.9	0.5	0.2	5.5	0.4	2.1	--	--	0.3	0.2	--	--
19	7.8	17.0	--	--	--	1.1	4.2	0.4	2.5	--	--	0.1	0.6	0.4	--
20	8.0	16.1	0.1	8.0	--	0.6	6.4	0.5	2.8	--	--	0.1	0.5	--	--
21	3.0	28.6	--	--	--	0.1	0.2	0.9	1.4	--	--	--	1.4	--	--
22	11.5	27.8	--	--	--	0.1	--	0.6	1.0	--	--	--	1.6	--	0.7

* No element found or below the detection limit of the instrument.

TABLE 7. Calculated Oxide Weight Percentages

Sample No.	Al_2O_3	SiO_2	MgO	CaO	TiO_2	Fe_2O_3	ZrO	BaO
1	19.8	49.6	--*	2.8	0.5	4.9	--	--
2	--	1.7	--	9.9	0.8	3.0	--	--
3	19.3	65.9	--	5.9	1.7	13.7	0.7	0.9
4	24.0	61.8	--	1.8	0.5	4.3	0.2	0.4
5	--	93.1	--	0.4	0.2	5.1	--	--
6	3.4	24.0	45.8	9.7	--	0.6	0.2	0.2
7	7.3	29.5	--	11.2	1.2	4.4	1.1	--
8	18.5	35.1	--	7.6	0.5	3.4	0.8	--
9	19.8	36.8	11.6	4.9	0.5	4.9	0.2	0.1
10	5.3	13.5	--	14.8	0.2	1.6	0.1	--
11	9.4	20.3	--	11.5	0.2	1.3	0.1	--
12	19.1	66.3	--	3.9	0.5	4.0	0.2	0.8
13	11.1	55.2	--	2.7	0.5	4.4	0.1	0.3
14	18.9	71.7	--	--	0.8	1.4	1.1	--
15	21.5	45.4	--	2.8	0.5	4.7	0.2	0.4
16	13.2	41.5	--	7.3	1.5	16.9	0.5	0.4
17	26.6	58.8	--	0.1	1.0	3.4	1.1	--
18	12.8	27.0	18.1	7.7	0.7	3.0	0.2	--
19	14.7	36.4	--	5.9	0.7	3.6	0.7	0.4
20	17.0	34.4	13.3	9.0	0.8	4.0	0.6	--
21	5.7	61.2	--	0.3	1.5	2.0	1.6	--
22	21.7	59.5	--	--	1.0	1.4	1.9	--

* No oxide found in the sample.

Absorbance bands indicative of mineral composition include the following:

Mineral Species	Wavenumbers
Calcium carbonate, $CaCO_3$	1,425; 871; 710
Dolomite, $CaMg(CO_3)_2$	1,440; 879; 725
Quartz, SiO_2	1,090; 799; 699
Kaolinite, $Al_2Si_2O_5(OH)_4$	1,100; 1,030; 910; 699
Montmorillonite, $(Na, Ca, Al, Mg)_2Si_4O_{10}(OH)_2$	1,040; 910
Talc, $3MgO\ 4SiO_2\ H_2O$	1,010; 660

A brief description of mineral composition and morphology of sands is provided below.

In general, sandy areas are produced by mechanical accumulations of minerals and rock fragments. The particles in these areas are products of surface weathering and erosion, and they consist of the disintegrated and decomposed debris of older rocks, transported and deposited by water, ice, or air. They are appropriately termed detrital or epiclastic materials. Most consist of quartz and silicate minerals such as clays. Influences of source and transportation are important in these deposits. Where erosion is slow, a residual blanket of thoroughly weathered material--a mature soil--accumulates over parent rock, and effects of climate may have more influence than even the composition of the parent rock on the character of the weathered product.

Where erosion is rapid, rock waste may be removed as soon as it is loosened from the bedrock, and little decomposition may occur before the material is carried away. Under such conditions, the mineral composition of detrital materials approximates that of the parent rock, and unstable minerals are to be expected.

During actual transportation, chemical changes in detrital sediments are negligible, but two very important physical effects are produced. Individual particles are generally altered in size, shape, and roundness by the abrasion and fracturing that result from rubbing and repeated impact of the particles on each other and on bedrock. Also, selective transportation, or sorting, affects the total aggregate of grains, so that particles tend to be segregated according to size, shape, and density.

The effect of these processes on the material is most clearly visible in the texture features, but is also evident in the mineral composition. When, in a sediment of particles of varied size, the sand is segregated from the clay, as commonly happens in natural sorting, the resulting deposits are mineralogically as well as texturally distinct. The clay material contains a relative concentration of clay minerals (kaolinite, montmorillonite, and illite), together with other micaceous minerals such as sericite and chlorite, whereas the sand is composed largely of quartz, with or without feldspars, ferromagnesium silicates, and rock fragments. Extensive well-sorted sands are most commonly deposited in terrestrial areas of drifting sand, or shallow parts of the sea and beaches, where the sand is continuously washed by wind or wave currents.

MONTMORILLONITE

Composition:	$(Na,Ca)_{0.33}(Al,Mg)_2Si_4O_{10}(OH)_2$	**Crystal System:**	Monoclinic
Source of Sample:	National Museum of Natural History Smithsonian Institution Washington, D.C.	**Occurrence:**	In bentonite clay deposits, soils and sedimentary and metamorphic rocks
Technique:	KBr Wafer		

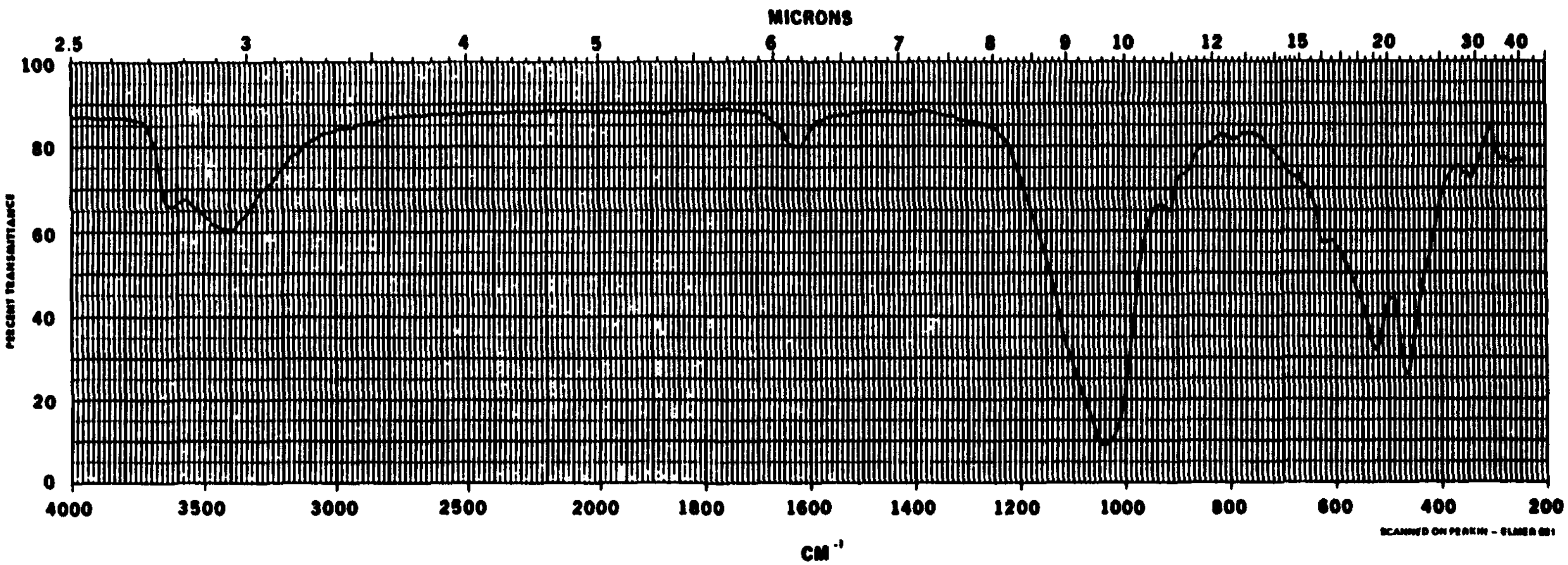

Figure 7. <u>Standard infrared spectrum for montmorillonite (clay)</u>

KAOLINITE

Composition:	$Al_2Si_2O_5(OH)_4$	Crystal System:	Triclinic
Source of Sample:	National Museum of Natural History Smithsonian Institution Washington, D.C.	Occurrence:	Mixed with feldspar and other aluminum silicates in soil and lake beds
Technique:	KBr Wafer		

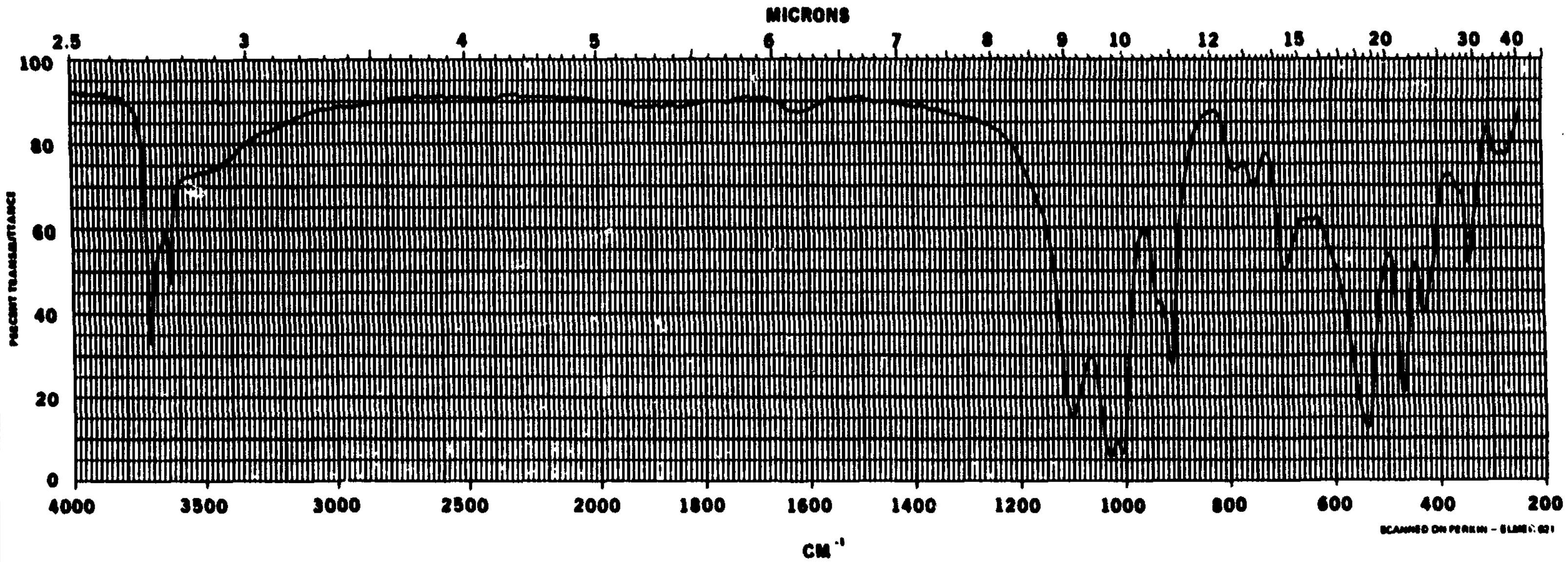

Figure 8. Standard infrared spectrum for kaolinite

QUARTZ

Composition:	SiO_2	Crystal System:	Hexagonal
Source of Sample:	National Museum of Natural History Smithsonian Institution Washington, D.C.	Occurrence:	In many igneous, metamorphic and sedimentary rocks and in sand and gravel deposits
Technique:	KBr Wafer		

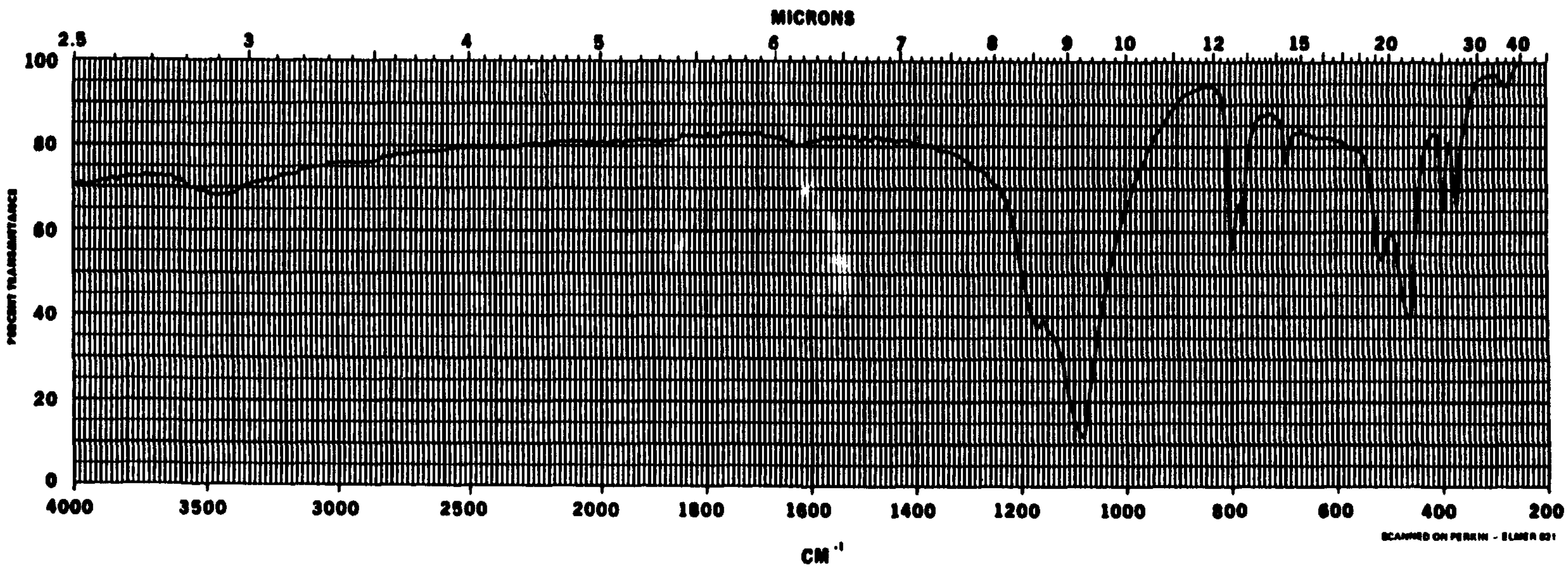

Figure 9. Standard infrared spectrum for quartz

CALCITE

Composition:	$CaCO_3$	Crystal System:	Hexagonal
Source of Sample:	National Museum of Natural History Smithsonian Institution Washington, D.C.	Occurrence:	In all limestones and marbles, in ore deposits, and as stalactites and stalagmites in caverns
Technique:	KBr Wafer	Impurities:	2040 cm^{-1}

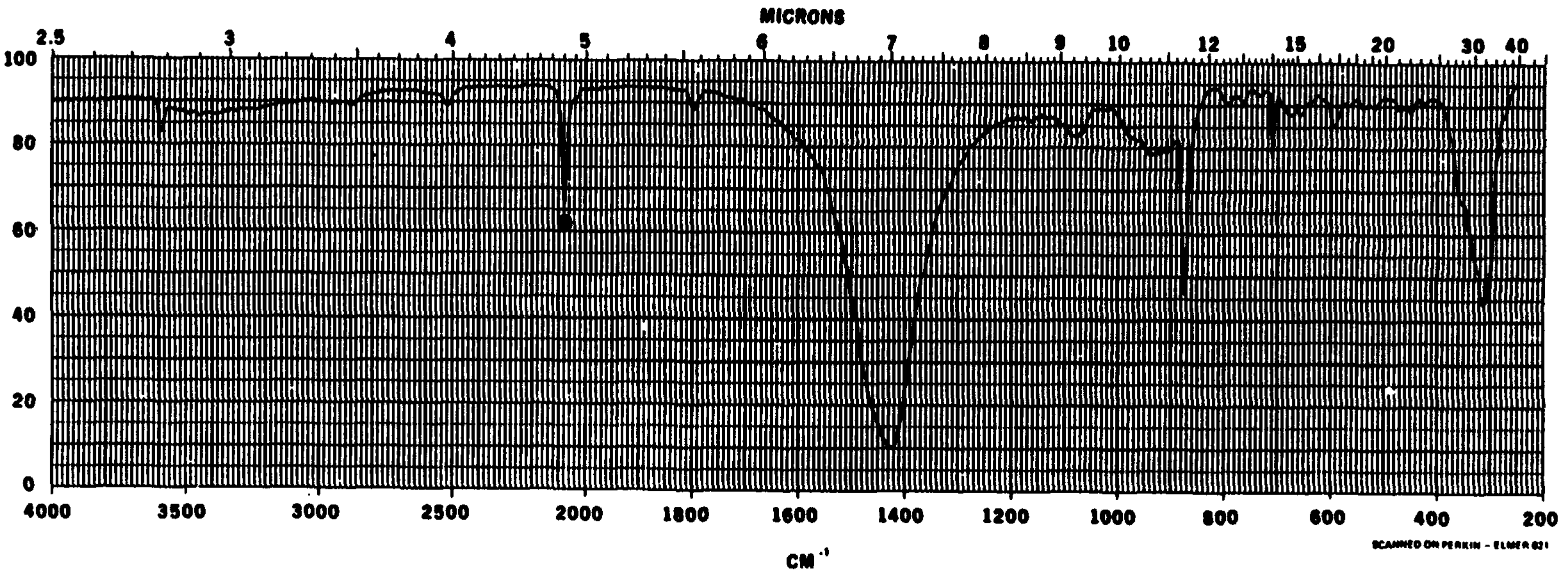

Figure 10. Standard infrared spectrum for calcite

ARAGONITE (Cianciano, Sicily)

Composition:	$CaCO_3$ Trimorphous with calcite and vaterite	**Crystal System:**	Orthorhombic
Source of Sample:	National Museum of Natural History Smithsonian Institution Washington, D.C.	**Occurrence:**	Low-temperature deposits near the surface; hot springs deposits; associated with gypsum and iron ore
Technique:	KBr Wafer		

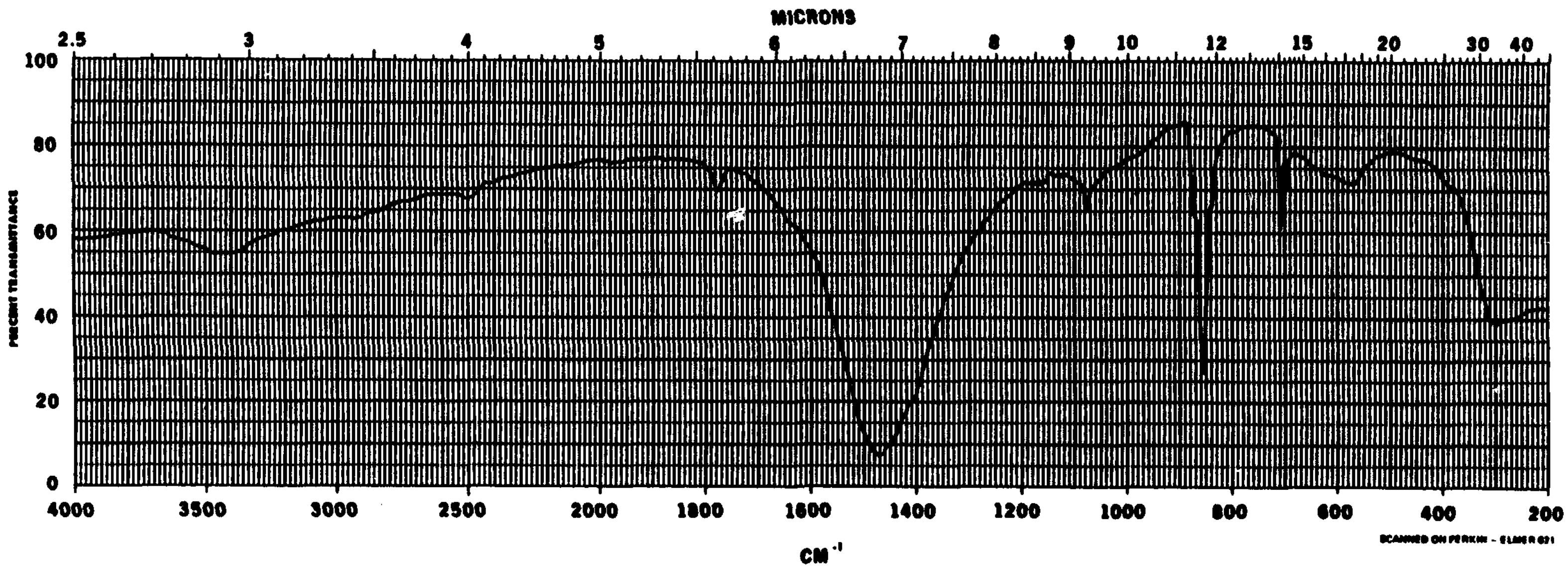

Figure 11. Standard infrared spectrum for aragonite

TALC — MAGNESIUM SILICATE, HYDRATE

Composition:	$3MgO \cdot 4SiO_2 \cdot H_2O$	Crystal System:	Monoclinic
Source of Sample:	Mallinckrodt, Inc. St. Louis, Missouri	Occurrence:	As an alteration of magnesium silicates such as olivine, pyroxenes, and amphiboles
Technique:	KBr Wafer		

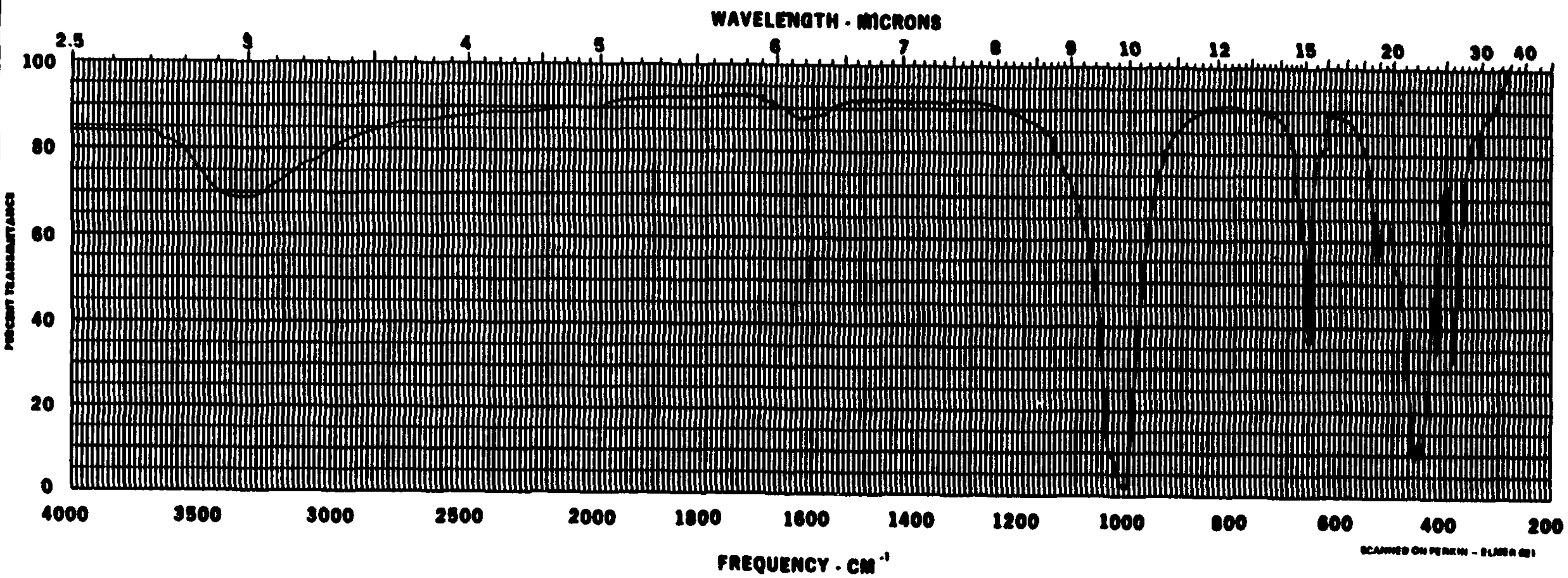

Figure 12. Standard infrared spectrum for talc

DOLOMITE

Composition: $CaMg(CO_3)_2$

Source of Sample: National Museum of Natural History
Smithsonian Institution
Washington, D.C.

Technique: KBr Wafer

Crystal System: Hexagonal

Occurrence: As extensive sedimentary strata; in veins in limestone or serpentine; in zinc veins associated with fluorite, calcite, barite and siderite

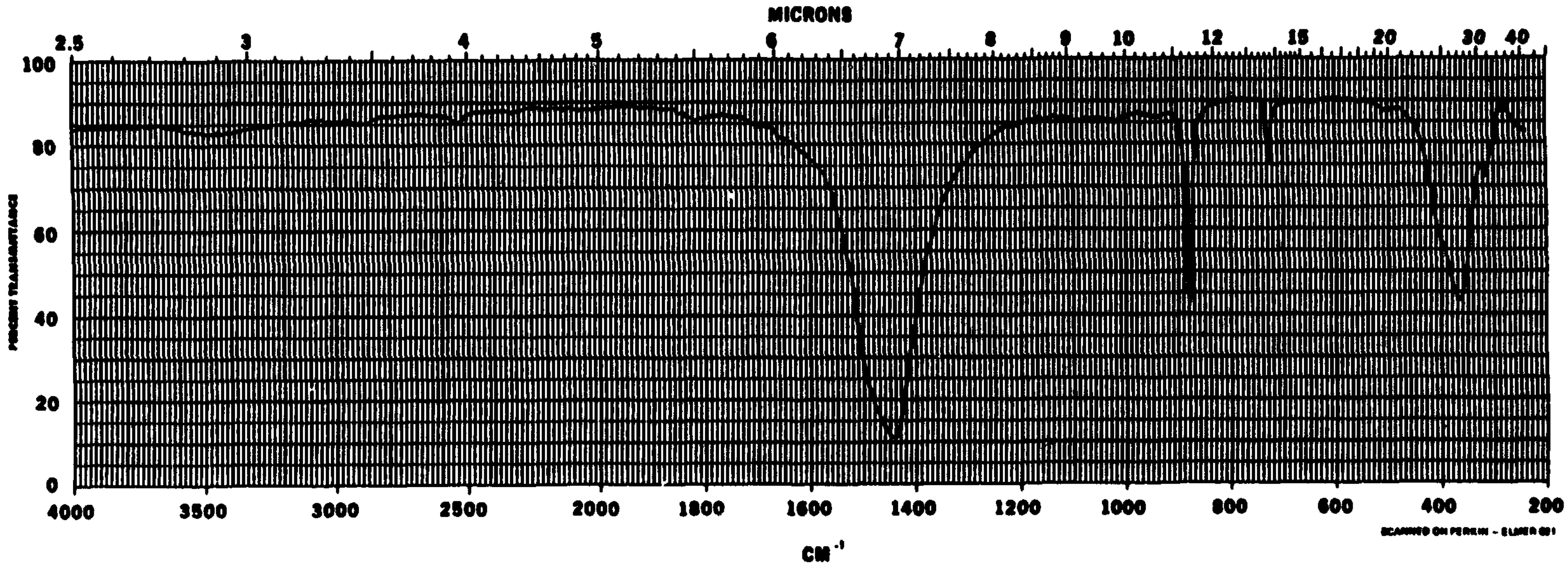

Figure 13. Standard infrared spectrum for dolomite

The effectiveness of abrasion in rounding grains is a function of mode and distance of transportation and also of size and kind of grains. It is greatest on the larger and softer grains, and is increased with distance of transportation. Crushing action on sediments will yield much more angular, sharp-cornered particles (Figs. 5 and 6), than will wind or water transport. Clastic grains are described in terms of particle diameter, sphericity and roundness.(7)

Fig. 14 illustrates the particle shape designations for grains, and TABLE 8, size designations. These terms are used to describe the particles shown in the electron microscopic photographs of the various sand locations used for this study.

Rock-forming minerals may be classified into general stability series to express resistance to destruction by normal processes, but the series varies with climatic conditions. Calcite, for example, is readily dissolved by surface solutions during weathering in warm humic regions where vegetation is abundant, but it is not so easily dissolved in arid regions where vegetation is scarce. Among the clay minerals formed by weathering, kaolinite is generally stable under

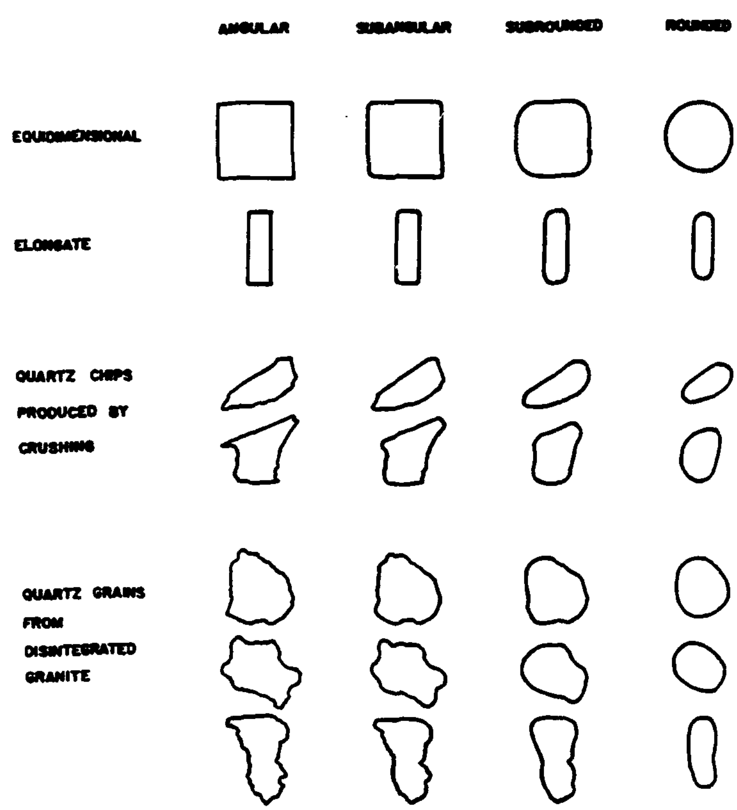

Figure 14. __Two-dimensional sphericity and roundness of grains (7)__

TABLE 8. Sand Shape Descriptions

Shape	Description
Angular	All corners sharp, having radius of curvature equal to zero; surface not abraded.
Subangular	Corners not sharp, but have very small radius of curvature; most of surface not abraded.
Subrounded	Corners very noticeably rounded, but surface not abraded.
Rounded	Entire surface is abraded; radius of curvature of the sharpest edges is about equal to radius of maximum inscribed circle.(7)

acid conditions, and montmorillonite under alkaline conditions. The most common detrital constituents are clay minerals, quartz, chert, muscovite, tourmaline, zircon, rutile, brookite, and anatase. Locally, some less common constituents may be so concentrated as to become principal components in particular deposits, such as gypsum, talc, or anhydrite.(7)

2. Description and Characterization by Microphotography

A combination characterization of the soil samples describing size, shape, and morphology from each location is presented below:

- Fort McClellan, AL

Grains are mainly equidimensional and range from angular to subangular. Particle sizes range from 5 to less than 3 micrometers. Infrared data are consistent with clay and carbonate minerals.

- Twentynine Palms, CA, Fuel Cell Debris

The fuel cell debris obtained from a stored military vehicle comprised mostly organic materials, rust, and fuel oxidation products. Very few sand particles were found in this sample.

- PTI Fine Test Dust

Grains range from 10 to 1 micrometers, with equidimensional and elongated, angular to subangular shapes. Infrared data shows largely clay composition, with a small quantity of carbonate minerals.

- AC Fine Test Dust

Grains range from 10 to less than one micrometer, with shapes from angular to subangular. Infrared spectrum is consistent with large quantities of clay, with small quantities of quartz and carbonate minerals.

- Fort Stewart, GA, Fuel Cell Debris

Insufficient sample to perform these analyses.

- Saudi Arabia 5 (AL-19625-X)

Grains are tabular, foliated in appearance, with vaguely hexagonal outlines. These particles are 10 micrometers or less and are rounded to subrounded in shape. Infrared data are consistent with largely carbonate minerals, with some talc present.

- Saudi Arabia 1 (AL-19535-X)

Grains are large, approximately 100 micrometers, and consistently elongated and angular-shaped. Infrared data show bands consistent with a largely dolomite and lesser amounts of clay mineral composition.

- Fort Polk, LA

Grains are largely subrounded, equidimensional tabular or foliated shapes, 10 micrometers or smaller. Infrared data show a composition consistent with a mixture of clay and carbonate minerals.

- Yuma Proving Ground, AZ

Grains range from 100 to less than 10 micrometers in size, with varying shapes including equidimensional angular particles and equidimensional subrounded particles, which differ in thickness and roundness. Infrared data show a composition consistent with a talc, clay, and carbonate mixture.

- Saudi Arabia 2 (AL-19536-X)

Grains show sizes from 10 to 2 micrometers, with equidimensional and elongated subangular particles, tabular, with delicate foliated structure observed. Infrared spectrum is consistent with calcium carbonate minerals, with lesser amounts of clay minerals.

- Fort Hood, TX, South Range

Grains are foliated, equidimensional, subangular, of approximately 10 micrometers. Infrared data show a large amount of carbonated minerals, with lesser amounts of clay minerals.

- AC Coarse Test Dust

Grains are angular, equidimensional particles with slightly foliated appearance. Infrared spectrum is consistent with large quantities of clay combined with small amounts of quartz and carbonate minerals.

- PTI Coarse Test Dust

Grains range from 60 to 3 micrometers, equidimensional with angular to subangular shapes. Infrared data show largely clay minerals, with small amounts of carbonate and some quartz minerals.

- Fort Stewart, GA, Red Cloud

Large foliated subrounded tabular grains of approximately 100 micrometers, with smaller 10-micrometer angular grains showing conchoidal fractures. Infrared data are consistent with quartz and clay minerals.

- Fort Irwin, CA, National Training Center (NTC)

Grains range from 100 micrometers, equidimensional, subrounded and flat, to 3- to 20-micrometer elongated, angular grains with conchoidal fractures. Infrared data are consistent with quartz and clay composition, with small amounts of carbonate minerals.

- Camp Pendleton, CA

Grains vary in size, but include elongated and equidimensional angular particles from 1 to 20 micrometers. Many grains show conchoidal fractures. Infrared data show only quartz absorbances, but oxide information and crystals indicate some calcite and clay particles.

- Fort Stewart, GA, Air Filter Debris

Larger grains of 100-micrometer size appear angular and smooth, while smaller, 10-micrometer particles have a crumbly appearance. Infrared data are consistent with clay minerals.

- Saudi Arabia 4 (AL-19624-X)

This sand sample shows large quantities of very fine, less than 2-micrometer grains of equidimensional angular form, with some larger 10-micrometer grains. The infrared spectrum is consistent with a mixture of aragonite and talc minerals.

- Fort Bliss, TX

Grains are divided between equidimensional 100-micrometer grains, subangular and smaller elongated, angular grains of 10 to 1 micrometer. Infrared data are consistent with clay and carbonate minerals.

- Saudi Arabia 3 (AL-19623-X)

Grains show a large variation in size, with less than 10-micrometer elongated, angular particles and up to 100-micrometer equidimensional, subrounded particles of layered appearance. Infrared spectrum is consistent with a talc and carbonate mixture.

- Fort Stewart, GA

Grains from 100 to 2 micrometers, angular, elongated, and equidimensional. Infrared data are consistent with a mixture of quartz and clay minerals.

- Fort Stewart, GA, Range 18553

Elongated, angular grains showing conchoidal fracture as seen in quartz minerals, along with large hexagonal particles showing some foliation. Infrared data show bands for silica as well as clay silicate minerals.

The soil samples fall into three elemental composition groupings. These groupings are shown in TABLE 9.

TABLE 9. Soil Groupings According to Elemental Analysis

High Calcium, no Magnesium Silicate	Saudi Arabia 1 Saudi Arabia 2 Ft. Hood, TX Camp Pendleton, CA Ft. Polk, LA
Magnesium Silicate	Saudi Arabia 3 Saudi Arabia 4 Saudi Arabia 5 Yuma Proving Ground, AZ
High Silica	Ft. Stewart, GA, Red Cloud Ft. Stewart, GA, Air Filter Debris Ft. Stewart, GA, Range 18553 Ft. Stewart, GA Ft. Irwin, CA Ft. McClellan, AL AC Fine Test Dust AC Coarse Test Dust PTI Fine Test Dust PTI Coarse Test Dust

D. Scanning Electron Microscope Characterization

Scanning electron microscope (SEM) photographs of all samples were taken, and Figs. 15 through 18 illustrate the different families of sand particles. Fig. 15 illustrates the family of soils containing a high calcium content (Saudi Arabia 1); Fig. 16 illustrates the magnesium silicate family (Saudi Arabia 5); and Fig. 17 illustrates the high silica content family [Ft. Stewart, GA, (Range 18553)]. Notice the large quartz particle in the bottom left corner of the photograph. Fig. 18 illustrates standardized, high silica test dust. The sample in this microphotograph is PTI Fine Test Dust. Other test dusts have similar shapes. Figs. 17 and 18 compare two soils that have the same elemental composition but different shapes and angularities. Additional SEM microphotographs are presented in Appendix B.

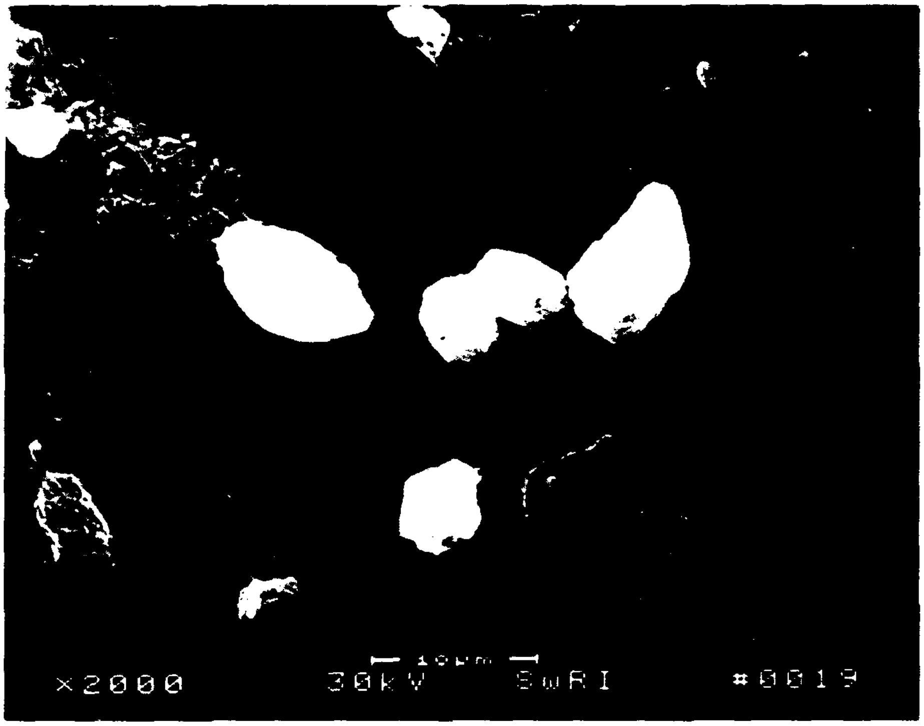

Figure 15. High calcium, Saudi Arabia 1

Figure 16. Magnesium silicate, Saudi Arabia 5

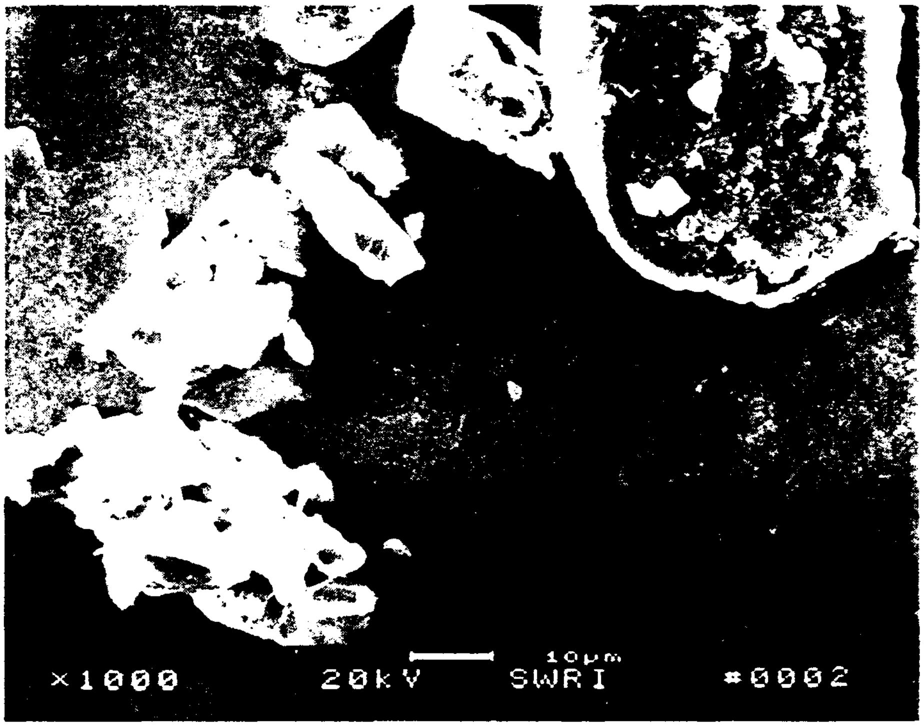

Figure 17. High silica, Ft. Stewart, GA (Range 18553)

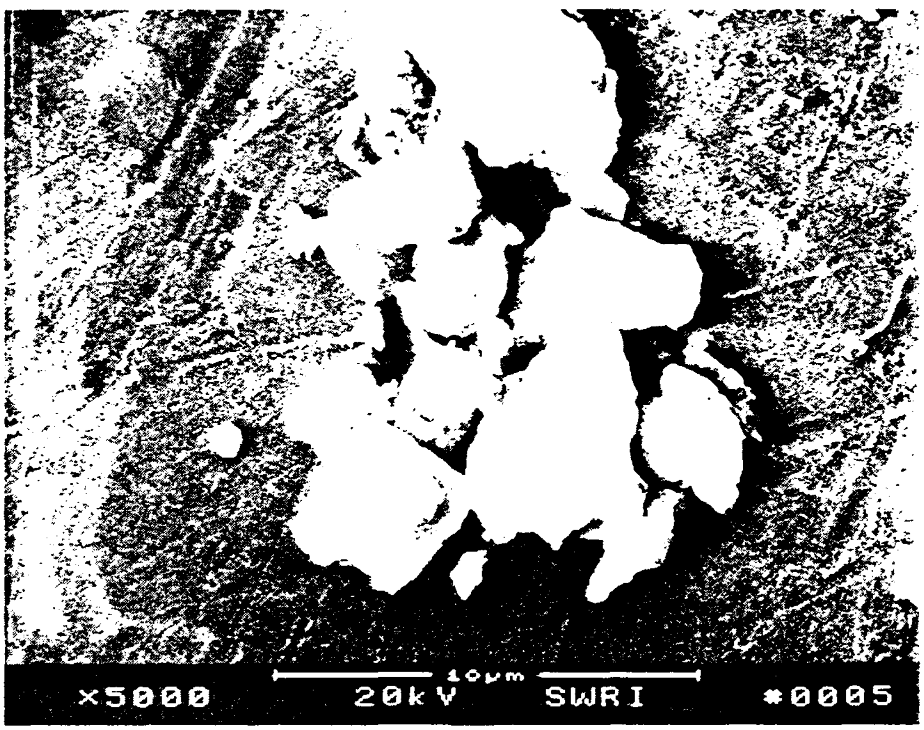

Figure 18. High silica, PTI fine test dust

E. Simulated Fuel Tank Demonstration

A simulated fuel tank demonstration was designed to determine the particle size distribution using typical fuel system parameters, Fig. 19. A 19-liter (5-gallon) can was filled with 15 liters (4 gallons) of test fluid (Viscor L4264V91) and 76 milligrams PTI Fine Test Dust (approximately 5 mg/L). The demonstration incorporated a closed system, with bypass and flow from the particle counter, returned to the top of the "fuel tank." This system simulates the return flow in a typical diesel engine. The pick-up line was placed 5 cm. (2 in.) from the bottom of the tank. Two tests were conducted:

1) The particulate debris was dispersed and the particle size distribution was determined without any agitation, except return flow. Data were recorded at 0, 1, 3, 5, and 8 hours.

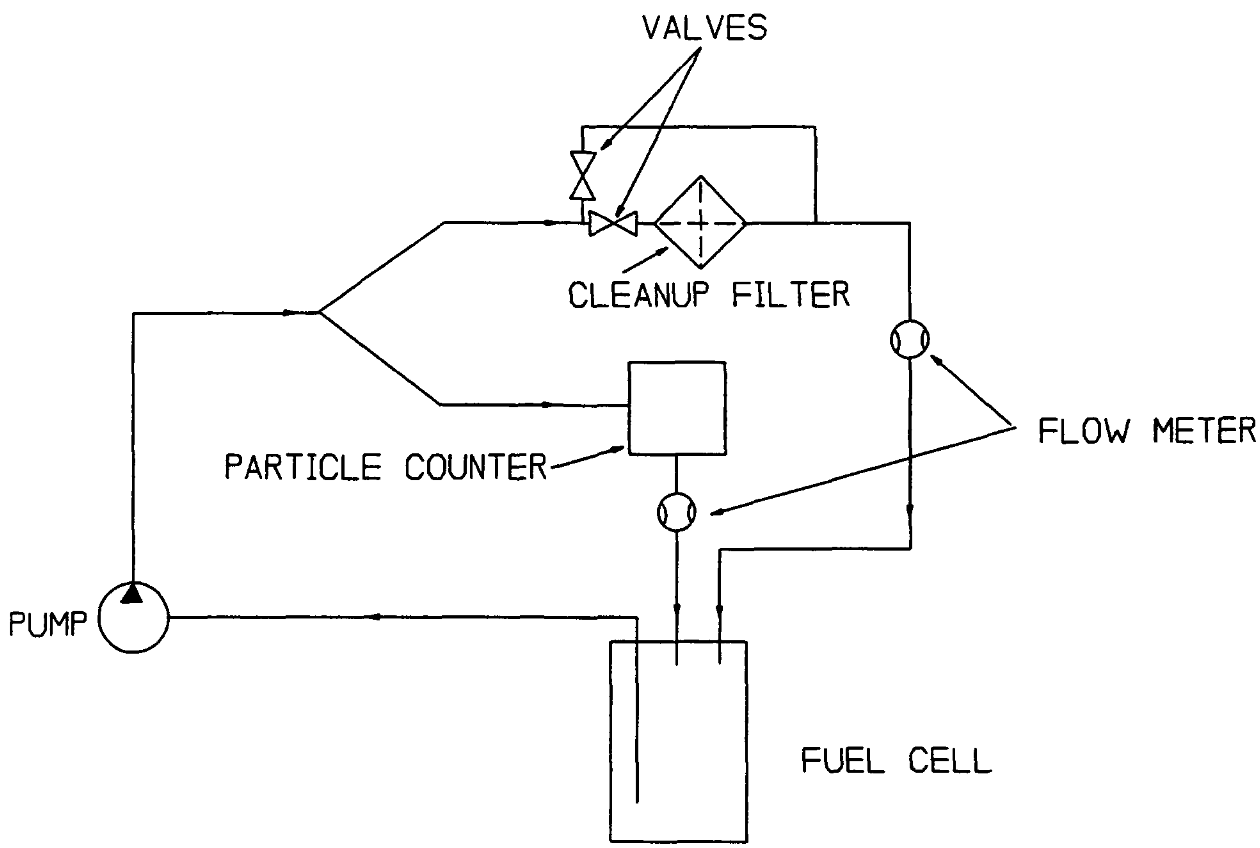

Figure 19. Simulated fuel tank design

2) The particle debris was dispers: d and the particle size distribution was determined with continuous return flow. Data were recorded every 15 minutes for 7 hours.

1. Static Demonstration

The particle size distributions for each sampling period are shown in Fig. 20. As expected, the larger particles (>20 micrometers) settled very rapidly, while the <10 micrometer particles stayed in suspension.

2. Dynamic Demonstration

The particle size distributions for various sampling periods are shown in Figs. 21 and 22. In Fig. 21, the distributions are shown for the first hour of the test. After a rapid decrease in concentration of particles, the system appeared to approach equilibrium. However, the concentration of particles less than 10 micrometers are being resuspended with the return flow

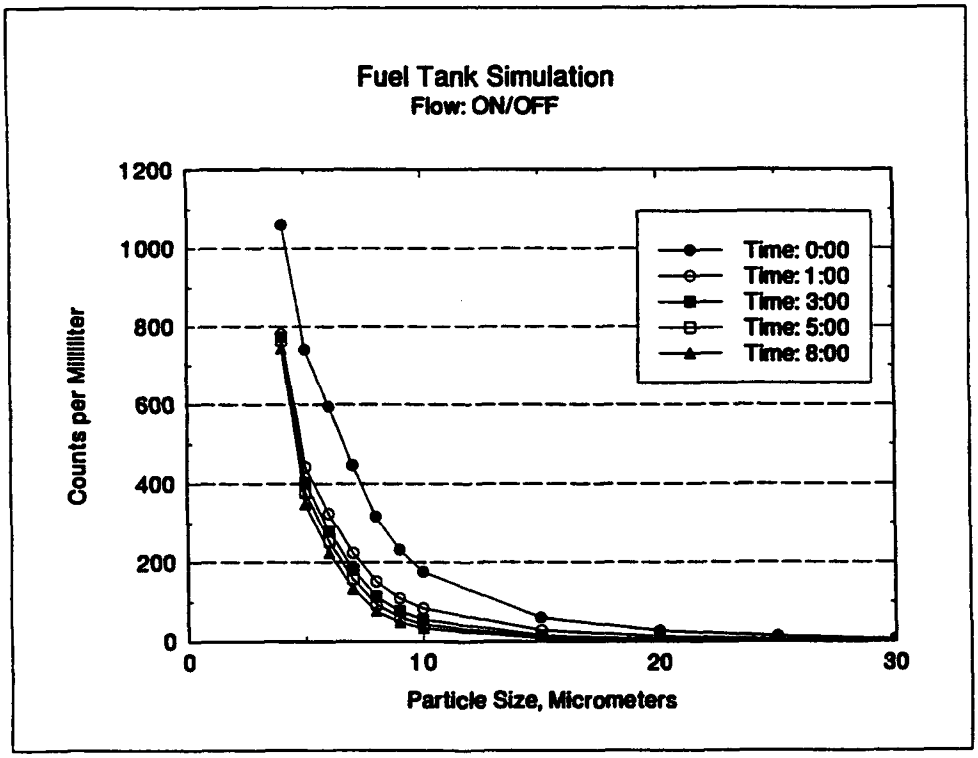

Figure 20. Static particle size distribution

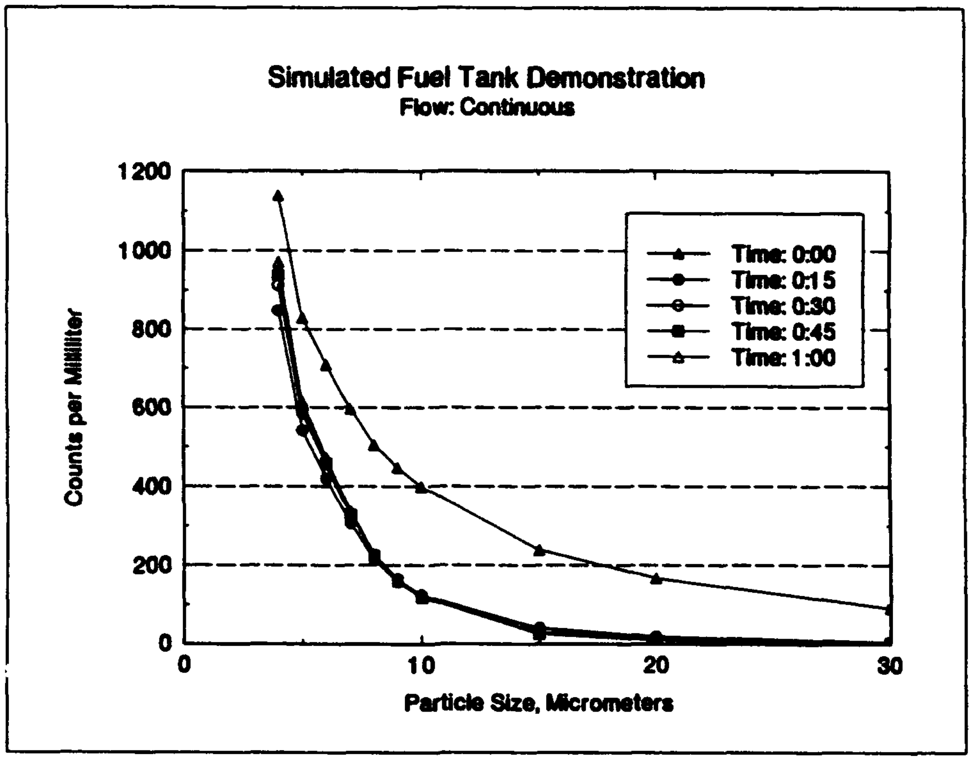

Figure 21. __Particle size distribution after 1 hour with continuous agitation__

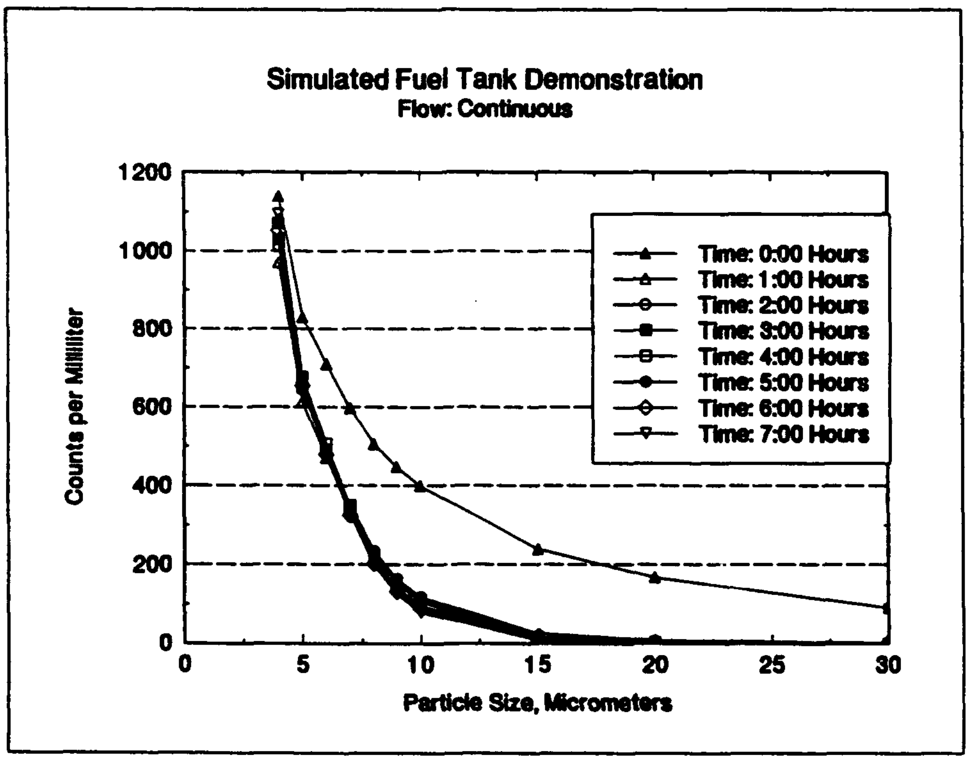

Figure 22. __Particle size distribution for 7 hours with continuous agitation__

agitation, while particles greater than 10 micrometers continue to settle to the bottom of the fuel tank. Fig. 22 displays the distributions at 1-hour intervals for the 7-hour test. The 4-micrometer particles continue to be resuspended with the return flow agitation; however, after approximately 6 hours, the return flow agitation no longer can suspend the greater than 6-micrometer particles.

Fig. 23 shows the comparison between static and dynamic flow conditions after 5 hours. Even though there is a large difference between the two tests for the smaller particles, particles greater than 15 micrometers have settled to the bottom of the fuel tank for both conditions. This pattern indicates that, under ormal driving conditions, particles greater than 15 micrometers will tend to remain on the bottom of the fuel tank, and will generally not encounter the filtration system.

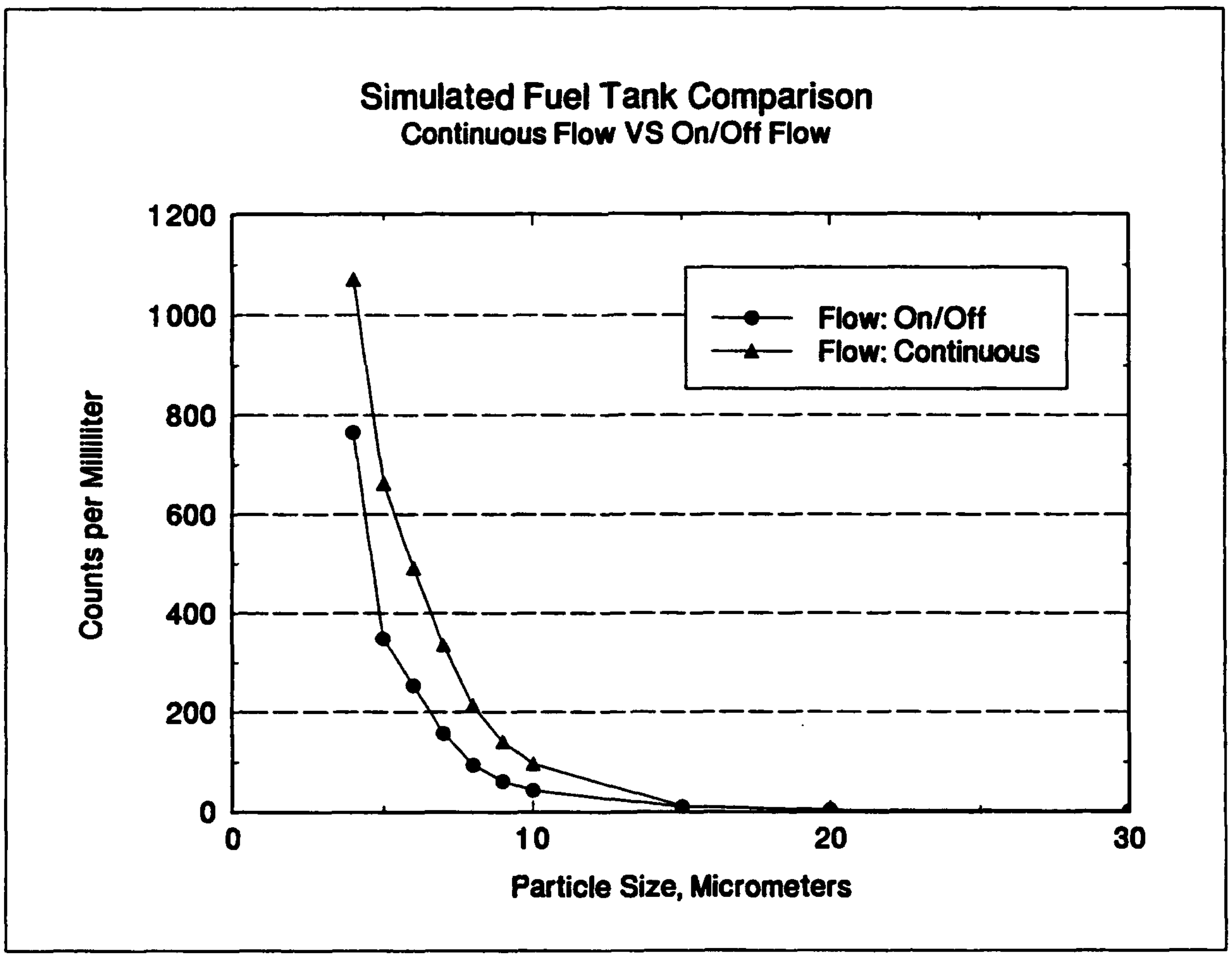

Figure 23. Static versus dynamic particle size distribution comparison at 5 hours

V. CONCLUSIONS AND RECOMMENDATIONS

This study indicated that soil from around the world varied widely in particle size distribution, composition, morphology, and angularity. Soils examined in this limited survey generally fell into three families: 1) high calcium, no magnesium silicate; 2) magnesium silicate; and 3) high silica. Only a limited amount of the sand samples matched standardized test dust compositions. It is recommended that further research be performed to determine if the sand samples examined differ with a larger population and to determine if different sand compositions have an adverse effect on filtration systems and other engine components. In addition, further studies need to identify the particle size distribution that fuel filters will encounter during normal operation. As illustrated in the fuel cell demonstrations, most particles larger than 15 micrometers settle to the bottom of the fuel cell. Particles greater than 20 micrometers create particle counting problems with keeping these particles suspended. It is felt that this size particle should not be incorporated into filtration test dusts. It is recommended that test dusts with particles ranging from 0 to 10 or 0 to 15 micrometers be evaluated for fuel filtration test dusts.

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VII. GLOSSARY

AC fine test dust	A fine siliceous test dust that has a known particle size distribution as specified by the manufacturer.
Airborne dust	Sand carried by or through the air; supported only by aerodynamic forces; aloft or flying.
Angularity	The quality or condition of having or forming sharp corners.
Anhydrite	Calcium sulfate, usually associated with gypsum, to which it alters. Differs from gypsum in being harder and lacking water of crystallization.
Brookite	Titanium dioxide. Identical in composition with rutile, but occurs in brown translucent orthorhombic crystals.
Calcite	Hexagonal (rhombohedral) calcium carbonate.
Chert	A dense cryptocrystalline rock; composed mineralogically of chalcedony (microcrystalline fibrous silica, and microfibrous amorphous silica or opal) and cryptocrystalline quartz; with a tough, splintery to conchoidal fracture and having numerous colors: white, gray, green, blue, pink, red, yellow, brown, or black.
Chlorite	A silicate of aluminum with ferrous iron and magnesium and chemically combined water, characterized by the green color common with silicates in which ferrous iron is prominent.
Clastic	A descriptive term applied to rock formed from fragments of other rocks.
Clay	An earthy deposit of extremely fine texture that is usually plastic when wet, and becomes hard and stone-like on being heated to redness. Chemically, it is characterized by containing hydrous silicates of alumina in considerable quantity, with feldspars and other silicates and quartz, and variable amounts of carbonates and ferruginous and organic matter. A portion of the constituents is generally in the colloidal state, and then acts as a lubricant to the grains and flakes of noncolloidal material.
Conchoidal	A material that produces smooth convexities or concavities, like those of a clamshell, when fractured.

Detrital rock	A rock made up of the debris of other rock.
Epiclastic	An adjective applied to clastic rocks formed by surface agencies. A general term applicable to several grades or types.
Feldspar	A general name for a group of abundant rock-forming minerals, the names and compositions of which are as follows: Orthoclase, a monoclinic potassium-aluminum silicate; varities are known as adularia and sanidine. Microcline, a triclinic variety of the same composition as orthoclase. Anorthoclase, a triclinic feldspar containing both sodium and potassium. Plagioclase feldspar are a subgroup of tricliic minerals, at one end of which is albite, a sodium-aluminum silicate, and at the other end anorthite, a calcium-aluminum silicate. Hyalophane is a monoclinic form containing barium and calcium. Feldspar is found in practically all igneous rocks.
Ferromagnesium	In petrology, containing iron and magnesium. Applied to certain dark silicate minerals, especially amphibole, pyroxene, biotite, and olivine, and other igneous rocks containing them as dominant constituents.
Filtration system	A system used to separate solid particles, impurities, from a liquid or gas by passing it through a porous substance.
Fine-grained soils	Silts and clays that have 50 percent or more pass the No. 200 sieve.
Foliated	A splitting into leaflike layers.
Gypsum	Hydrous calcium sulphate. Alabaster is a fine-grained compact variety, white, shade, or tinted. Gypsite is an incoherent mass of very small gypsum crystals or particles, and has a soft, earthy appearance; contains various impurities, generally silica or clay. Satin spar is a fibrous variety with a pearly, opalescent appearance. Selenite is a variety that occurs in distinct crystals or in broad folia. Some crystals are 3 or 4 feet long and clear thoughout.
Humic	Of, pertaining to, or derived from humus.
Humus	A dark brown substance, formed usually in soil, due to the partial decomposition of vegetal matter; the organic portion of the soil.
Illite	A general term for the clay-mineral constituent of araillaceous sediments belonging to the micagroup. Occurs in micaceous particles less than 1 micrometer. Gray, light green, or yellowish brown. A silicate of potassium, aluminum, iron, and magnesium, with water.
Kaolinite	The hydrated silicate of alumina, which is the base of clays and which gives them plasticity. When kaolinite is mingled with varying amounts

of comminuted quartz, and yields a pure white clay, the mixture is kaolin.

Mica — A hydrous silicate having a very fine basal cleavage that renders it capable of being split into thin, tough, transparent plates. The most common varieties are muscovite and biotite.

Micaceous — Characteristic of, pertaining to, or containing mica.

Montmorillonite — Very soft and tender, clay-like. Luster feeble. Color white or grayish to rose-red and bluish; also pistachio green.

Muscovite — Potash-bearing, white mica.

PTI test dust — Replacement for AC Test Dust, the standardized test dust used for filtration evaluation.

Quartz — Crystallized silicon dioxide. <u>Amethyst</u> is a variety of the well known amethystine color. <u>Aventurine</u> is a quartz spangled with scales of mica, hematite, or other minerals. <u>False topaz</u> or <u>citrine</u> is a yellow quartz. <u>Rock crystal</u> is a watery clear variety. <u>Rose quartz</u> is a pink variety. <u>Rutilated quartz</u> contains needles of rutile.

Rutile — Titanium dioxide, tetragonal. Crystals are commonly prismatic, vertically striated or furrowed; often slender acicular. Occasionally compact, massive.

Sericite — A more or less fibrous form of muscovite (potash mica), often resulting from the alteration of feldspar.

Silicate — A salt or ester of any of the silicic acids. In mineralogical chemistry, the silicates are of great importance, forming by far the largest group of minerals.

Silt — Soil passing a No. 200 (75 micrometer) U.S. standard sieve that is nonplastic or very slightly plastic and that exhibits little or no strength when air dry.

Sonicate — Mixing, using the energy produced by sound waves.

Talc — A hydrous silicate of alumina, magnesia, and iron. Hardness of 1, feels greasy, and structure usually foliated.

Tourmaline — A complex aluminum silicate of hexagonal crystallization containing boron and, in some varieties, lithium and other elements. It occurs in long, usually striated prisms in ancient crystalline rocks.

Viscor L4264V91	Hydrocarbon fluid used to simulate automotive fluids. Used commonly in filtration testing.
Zircon	Zirconium silicate.

VIII. ACRONYMS AND ABBREVIATIONS

ACFTD	- Air Cleaner Fine Test Dust produced by AC Rochester
ACCTD	- Air Cleaner Coarse Test Dust produced by AC Rochester
ATR	- Attenuated Total Reflectance
BFLRF	- Belvoir Fuels and Lubricants Research Facility (SwRI)
Belvoir RDE Center	- U.S. Army Belvoir Research, Development and Engineering Center
CONUS	- Continental United States
CUCV	- Commercial Utility Cargo Vehicle
FTIR	- Fourier Transform Infrared Spectrophotometer
HMMWV	- High Mobility Multipurpose Wheeled Vehicle
LAV	- U.S. Marines Light Armored Vehicle
PTI	- Powder Technology Incorporated
SEM	- Scanning Electron Microscope
SwRI	- Southwest Research Institute

APPENDIX A

Soil Sample FTIR Spectra

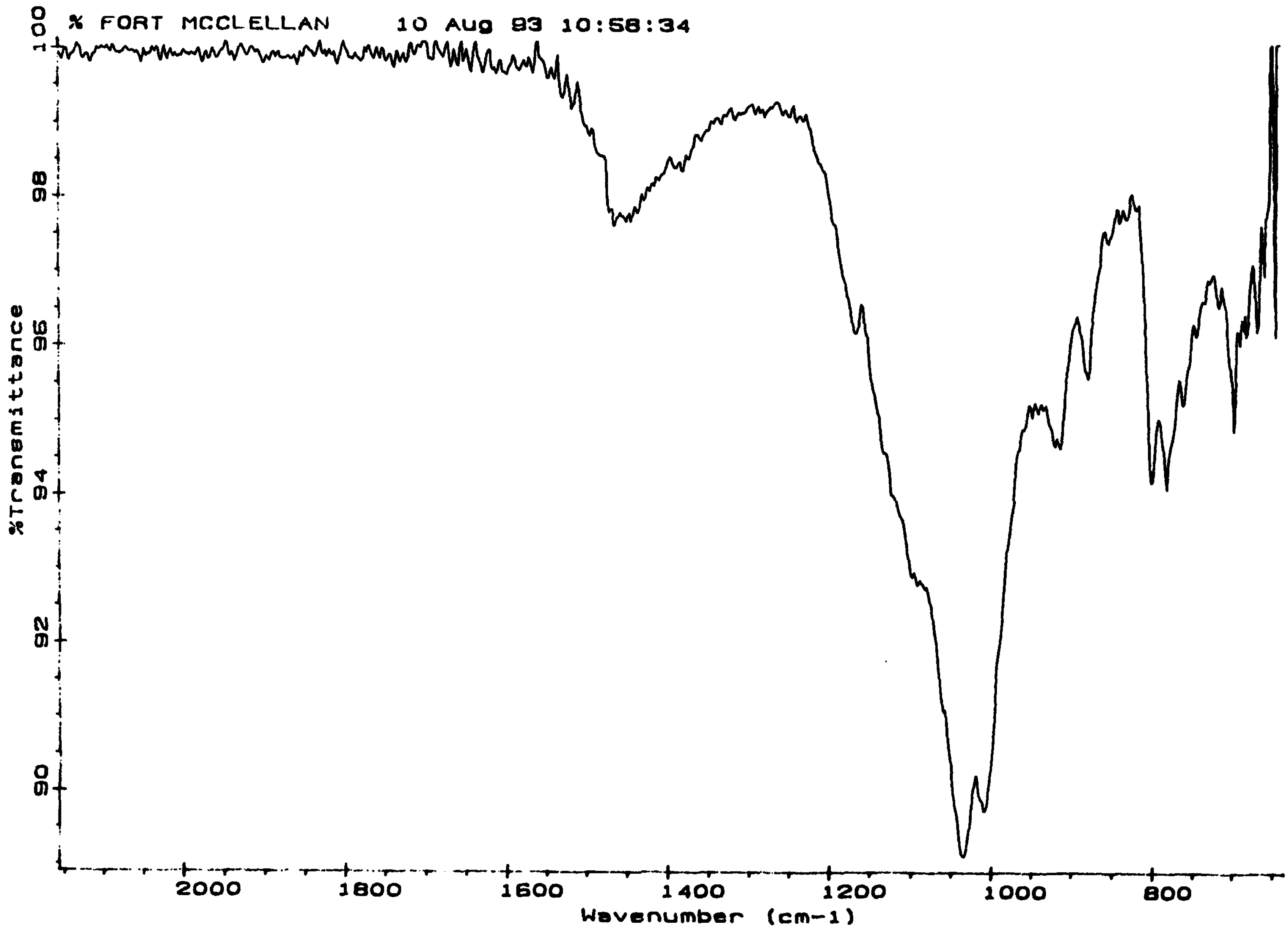

Figure A-1. Ft. McClellan, AL, infrared spectrum

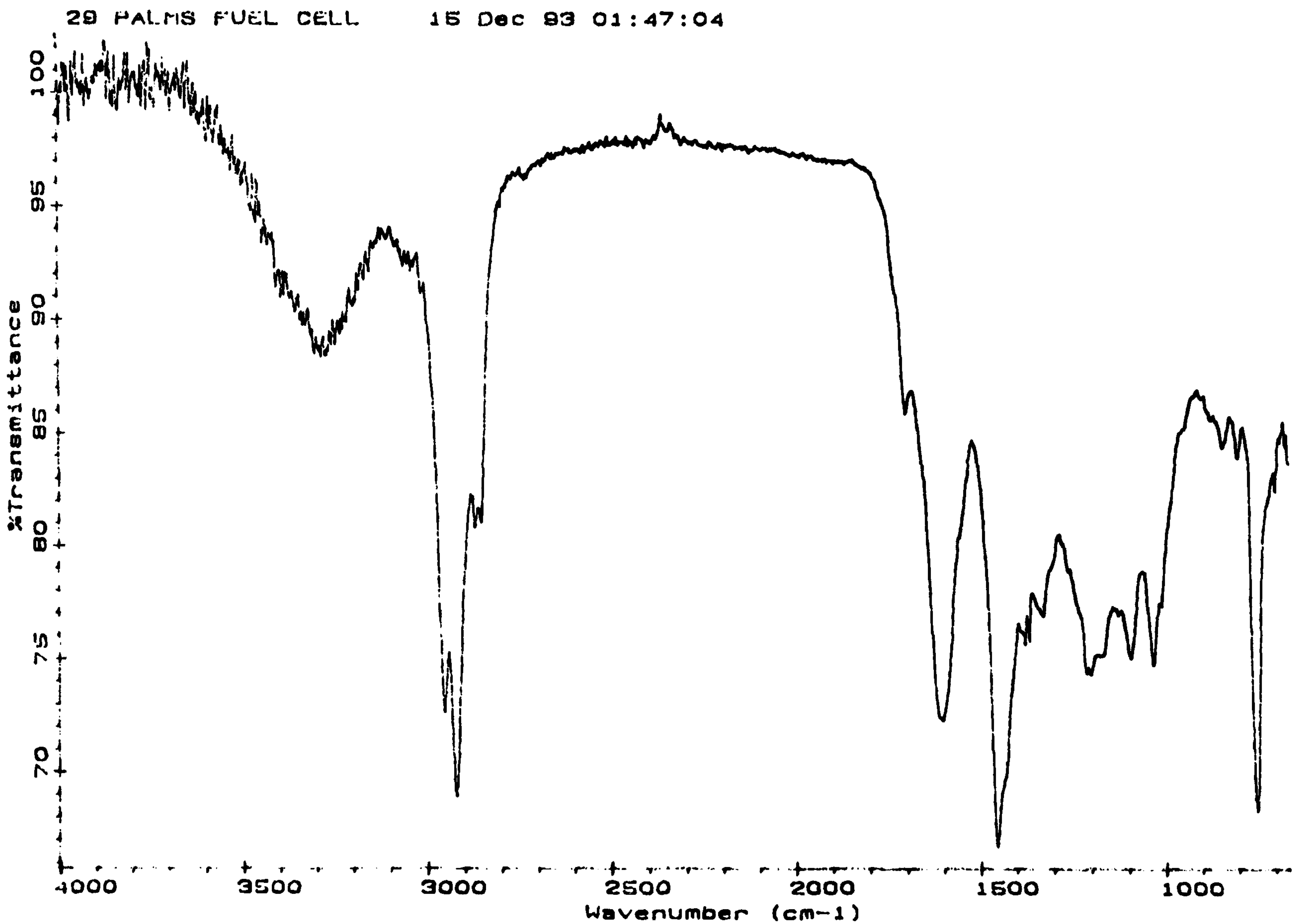

Figure A-2. __Twentynine Palms, CA, infrared spectrum__

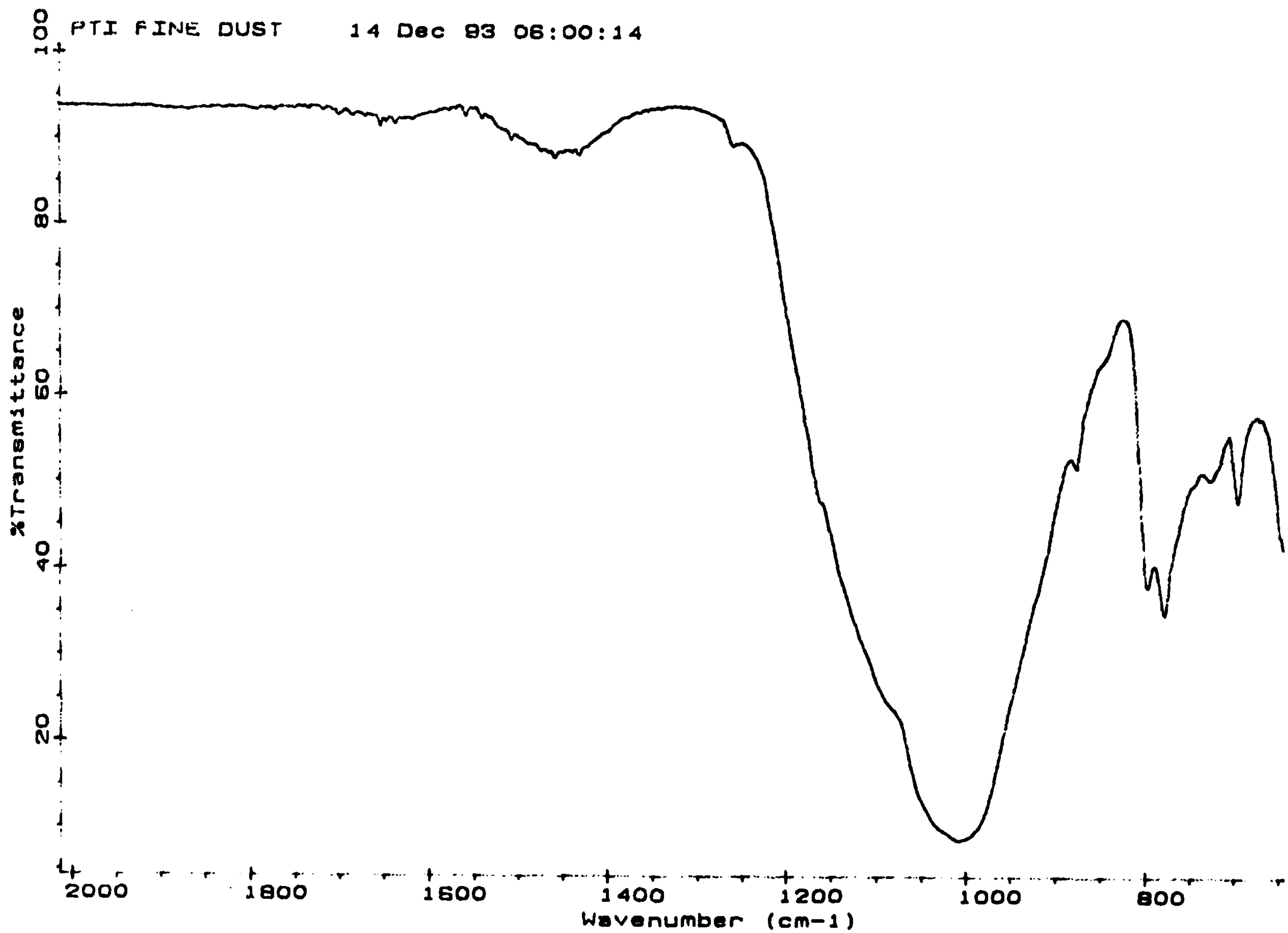

Figure A-3. **<u>PTI fine test dust infrared spectrum</u>**

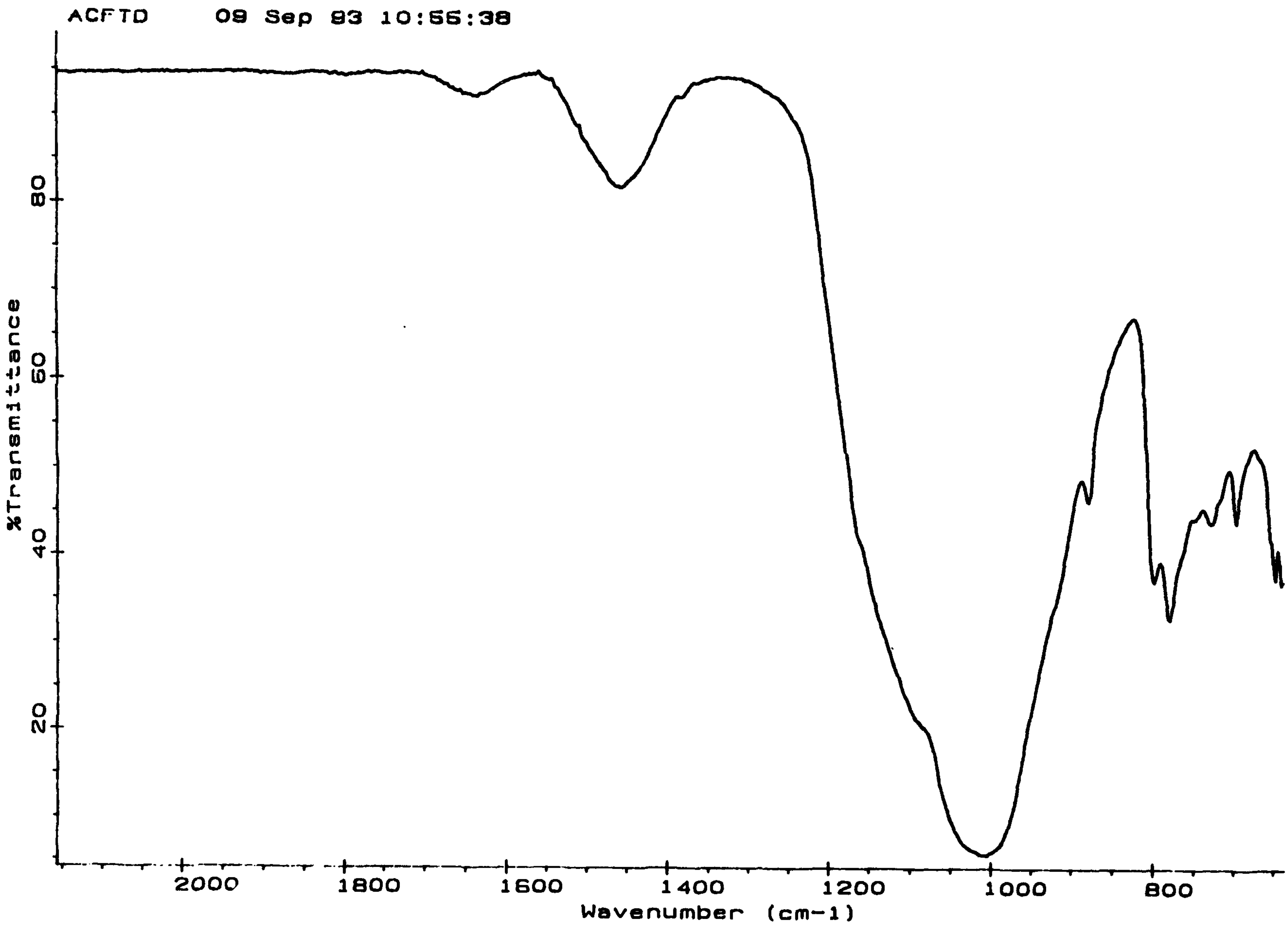

Figure A-4. AC fine test dust infrared spectrum

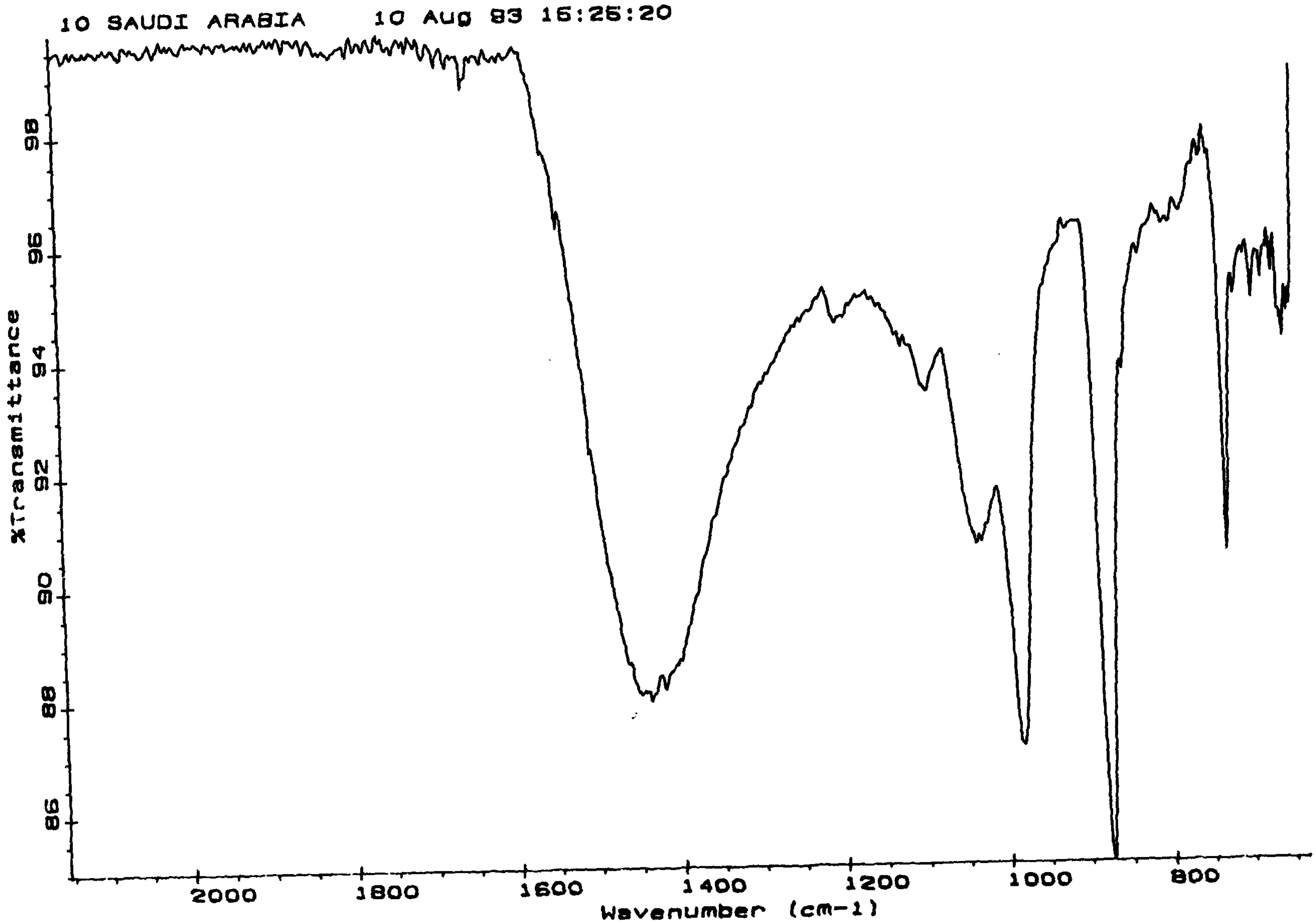

Figure A-5. Saudi Arabia 5 infrared spectrum

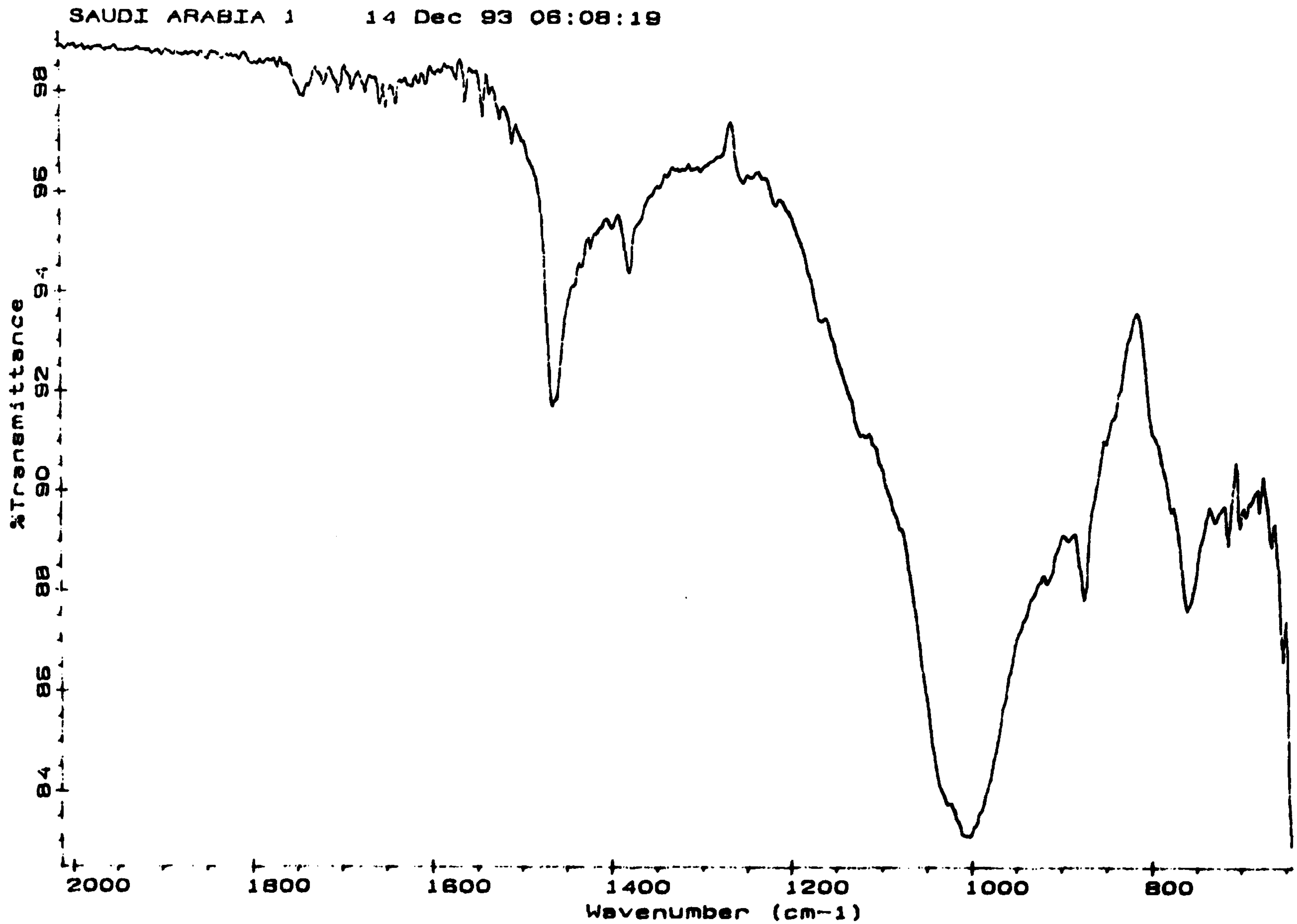

Figure A-6. <u>Saudi Arabia 1 infrared spectrum</u>

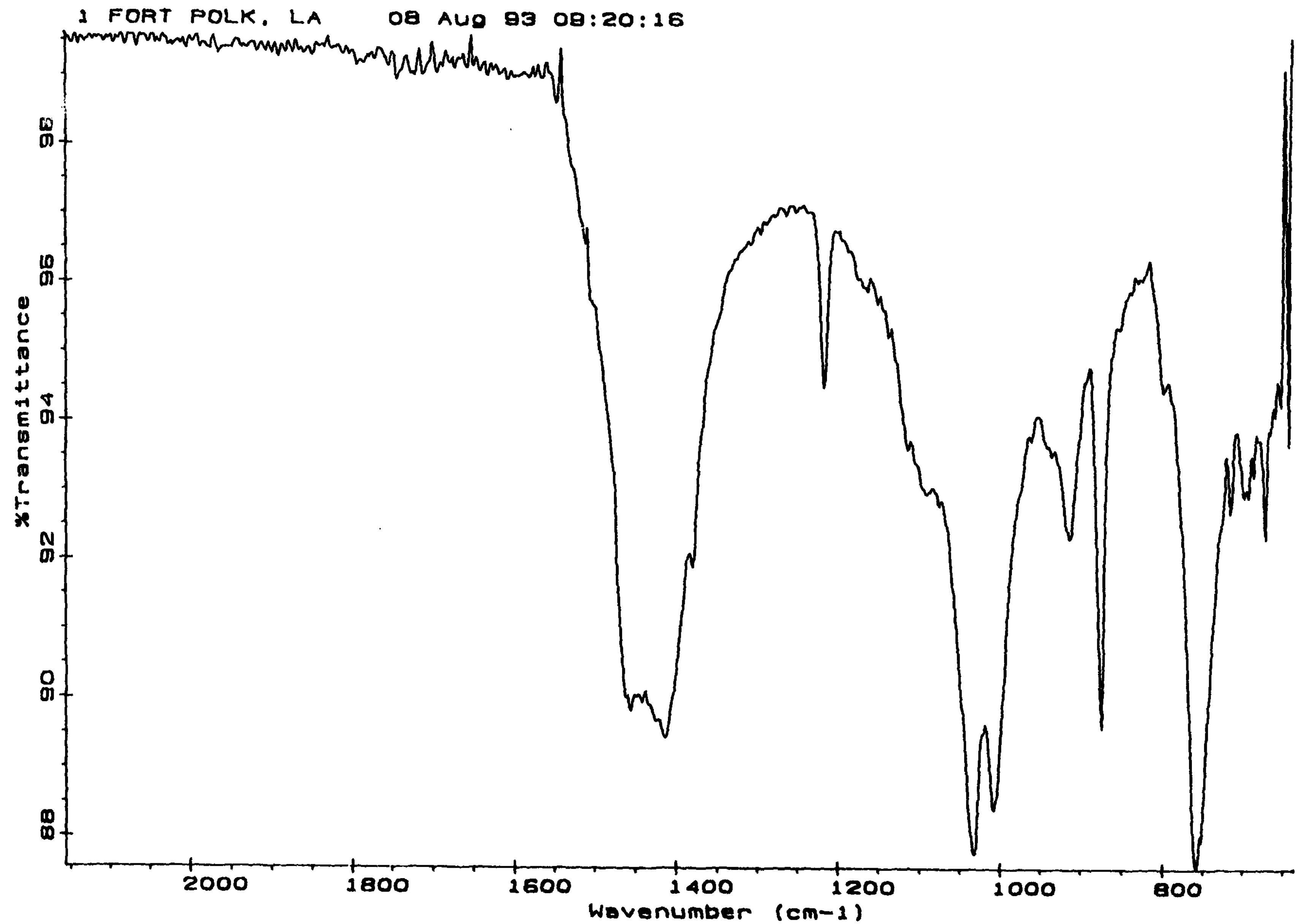

Figure A-7. <u>Ft. Polk, LA, infrared spectrum</u>

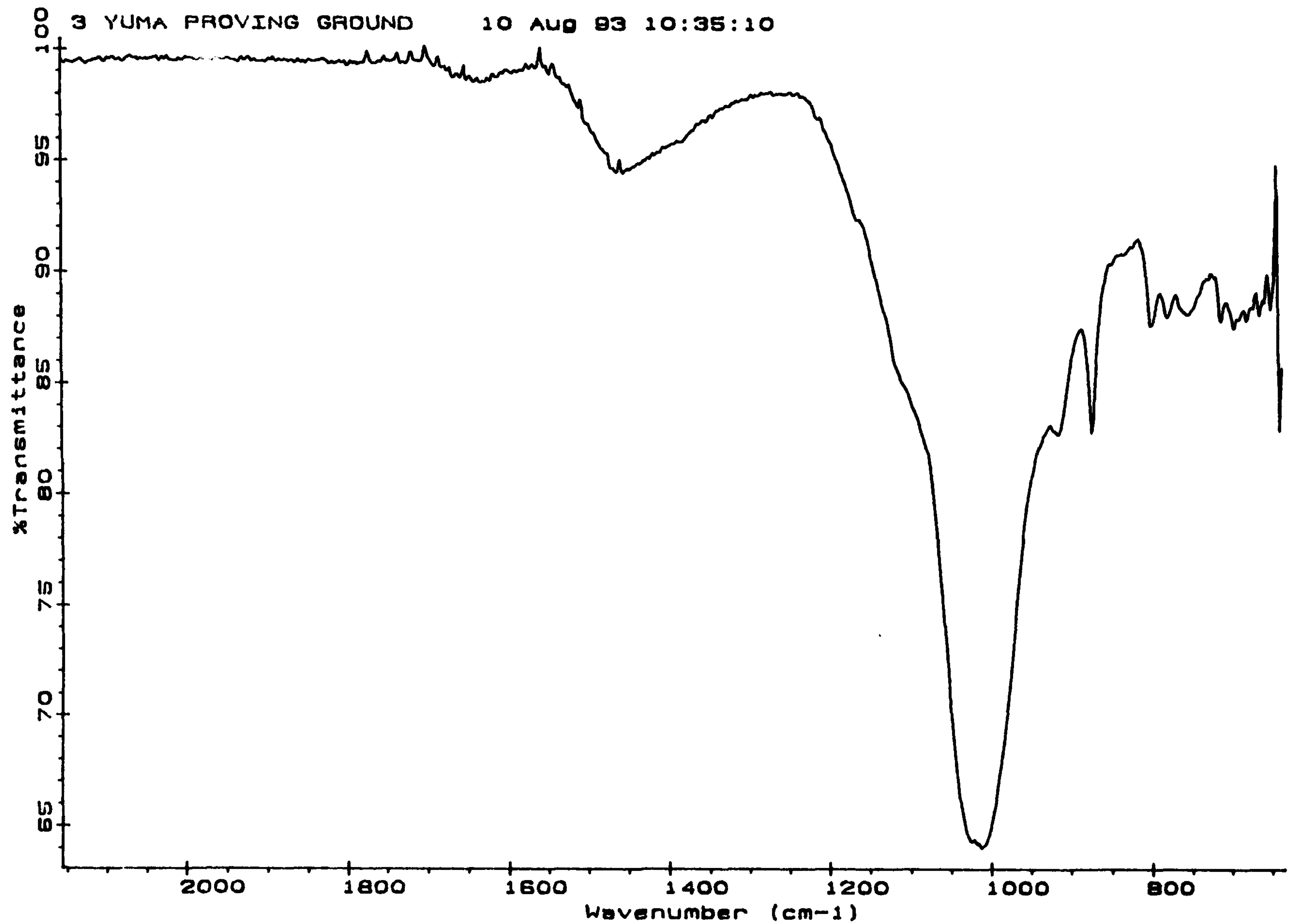

Figure A-8. Yuma Proving Ground, AZ, infrared spectrum

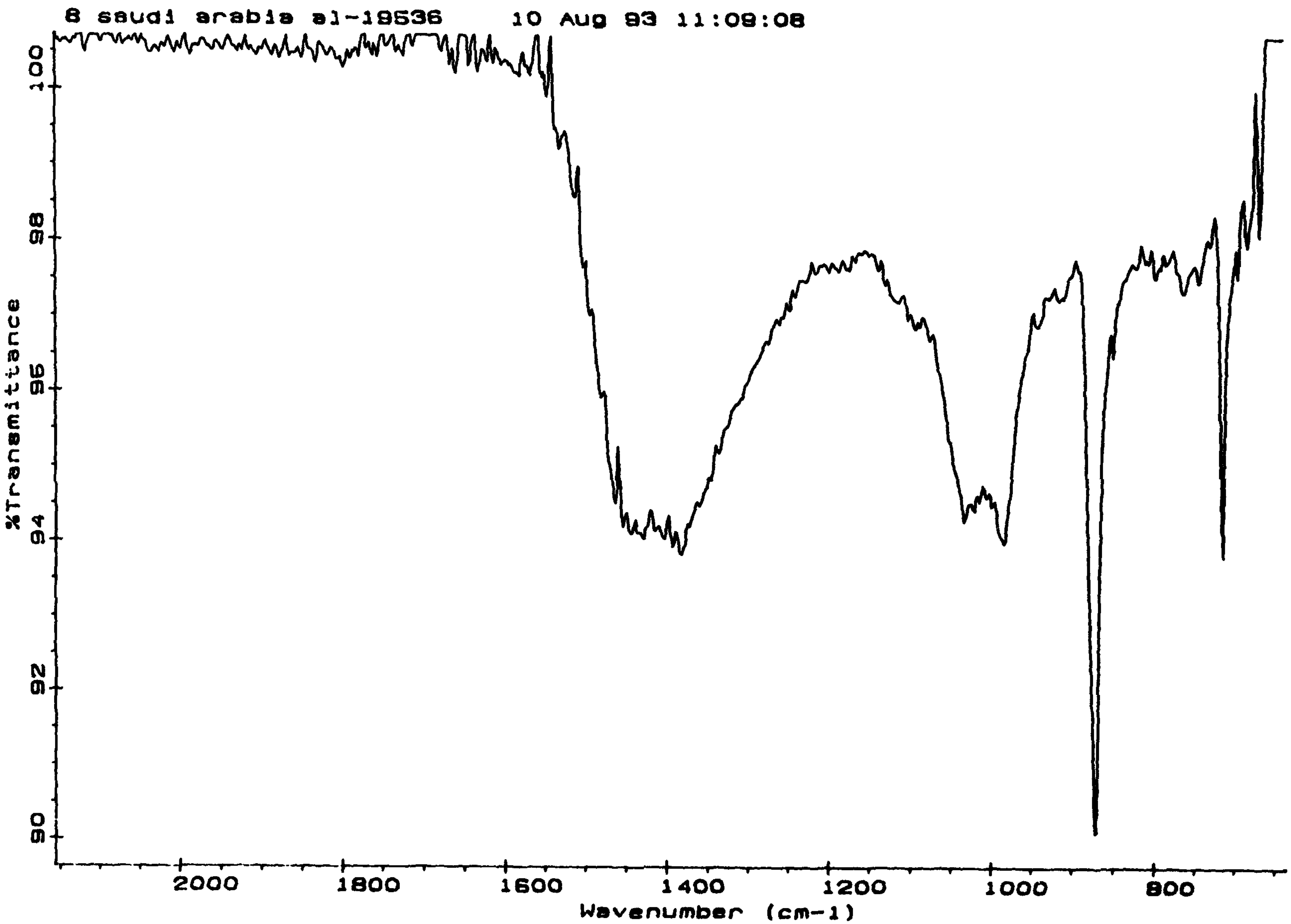

Figure A-9. <u>Saudi Arabia 2 infrared spectrum</u>

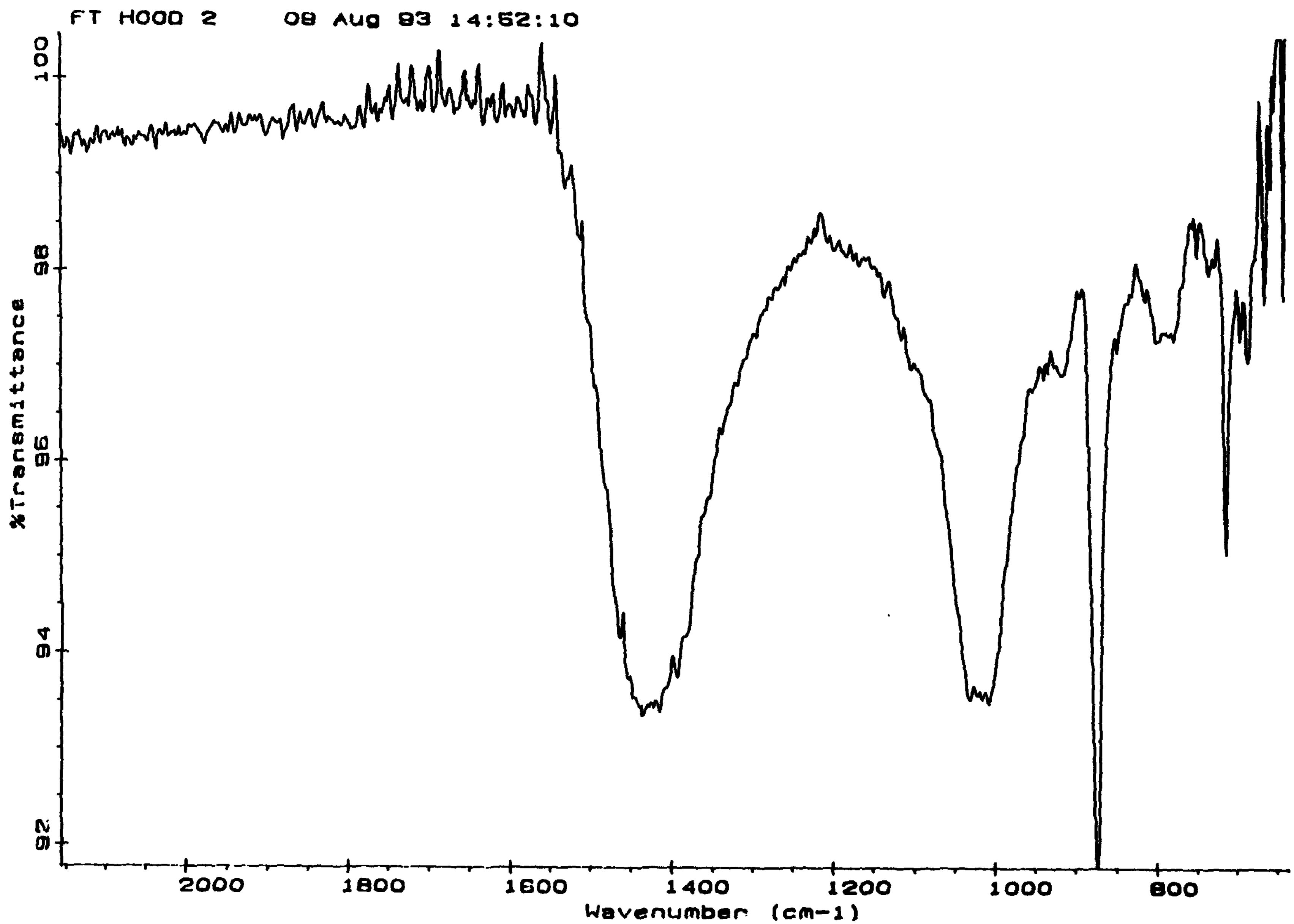

Figure A-10. __Ft. Hood, TX, infrared spectrum__

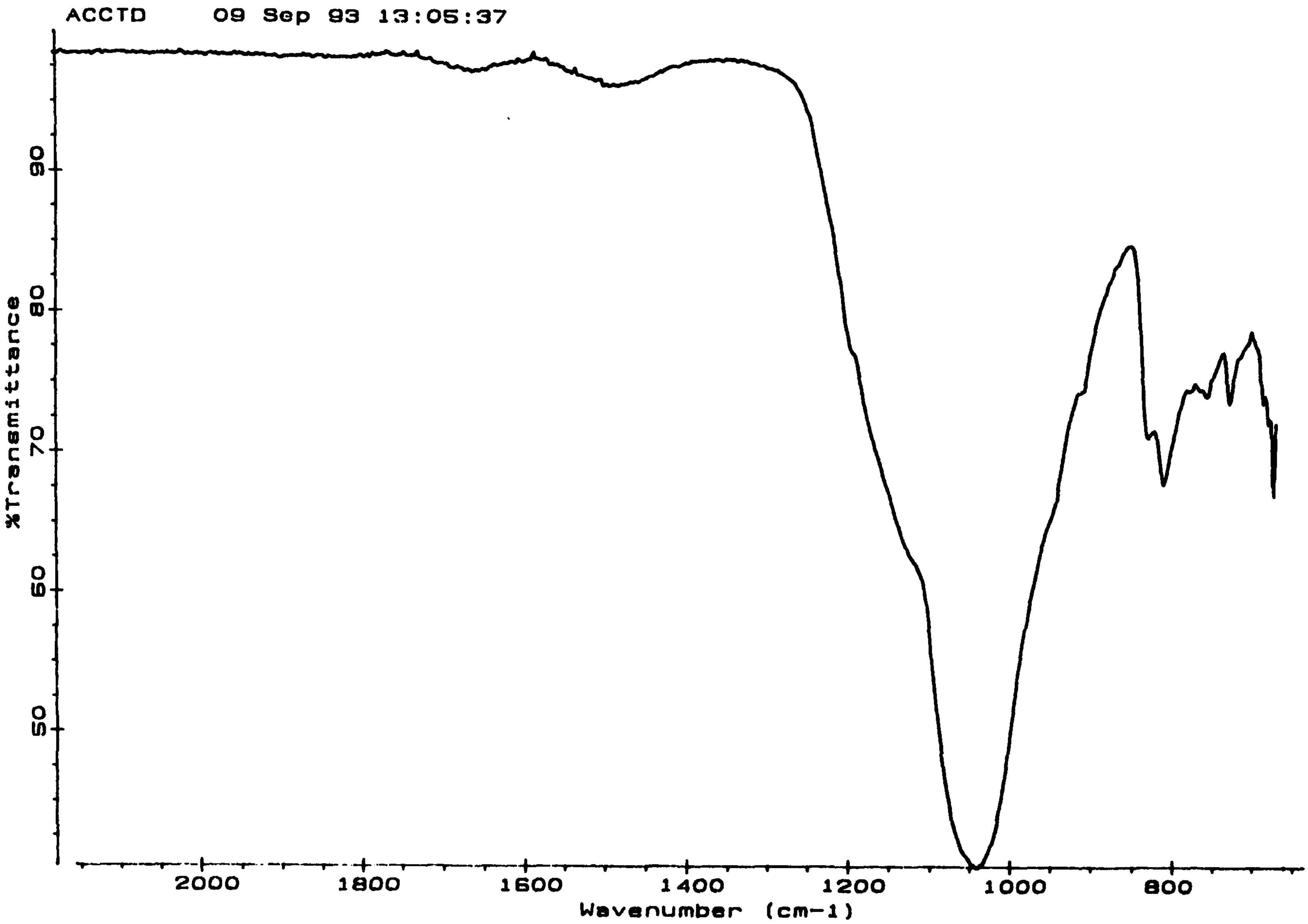

Figure A-11. <u>AC coarse test dust infrared spectrum</u>

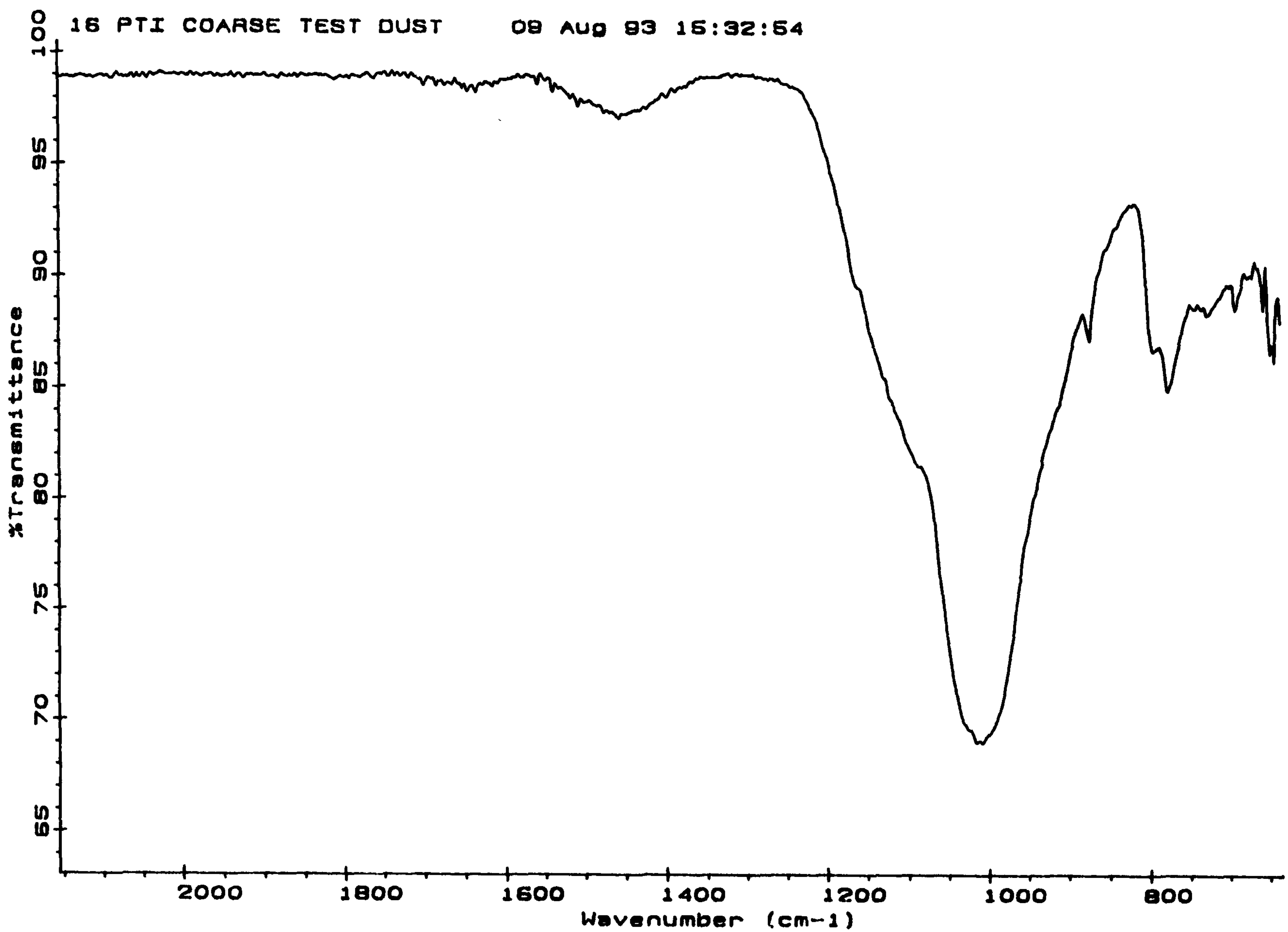

Figure A-12. <u>PTI coarse test dust infrared spectrum</u>

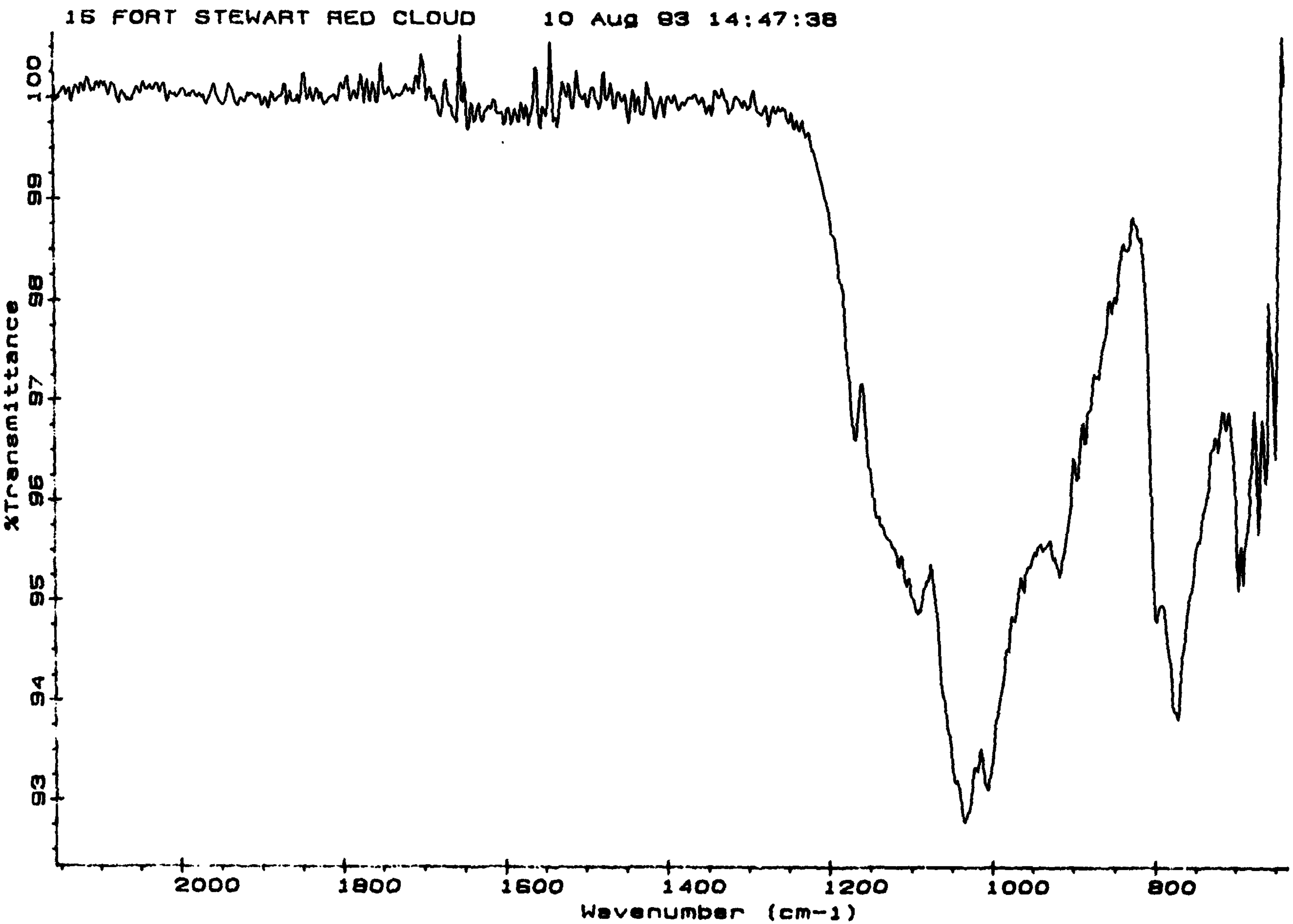

Figure A-13. Ft. Stewart, GA, Red Cloud, infrared spectrum

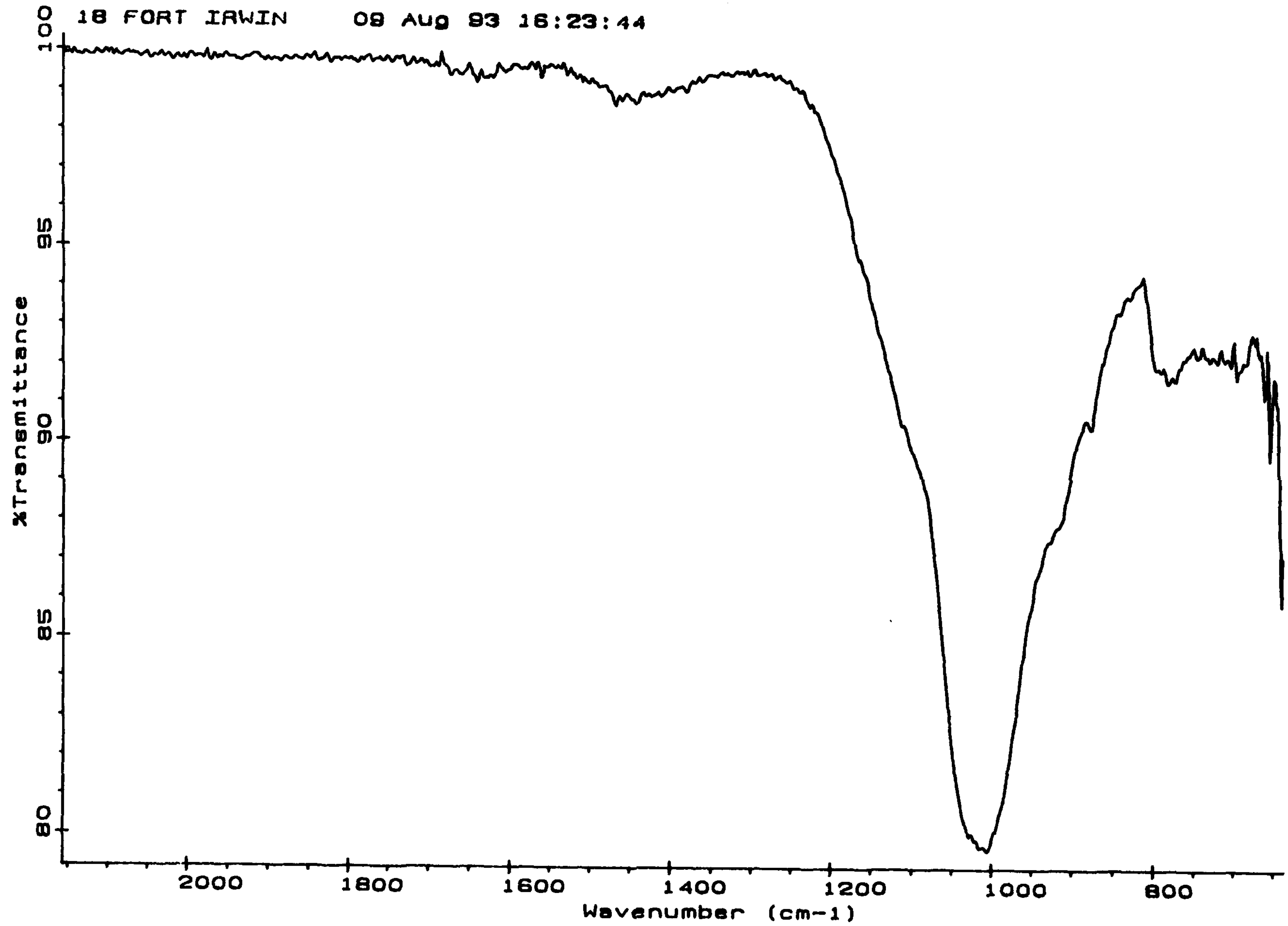

Figure A-14. Ft. Irwin, CA, infrared spectrum

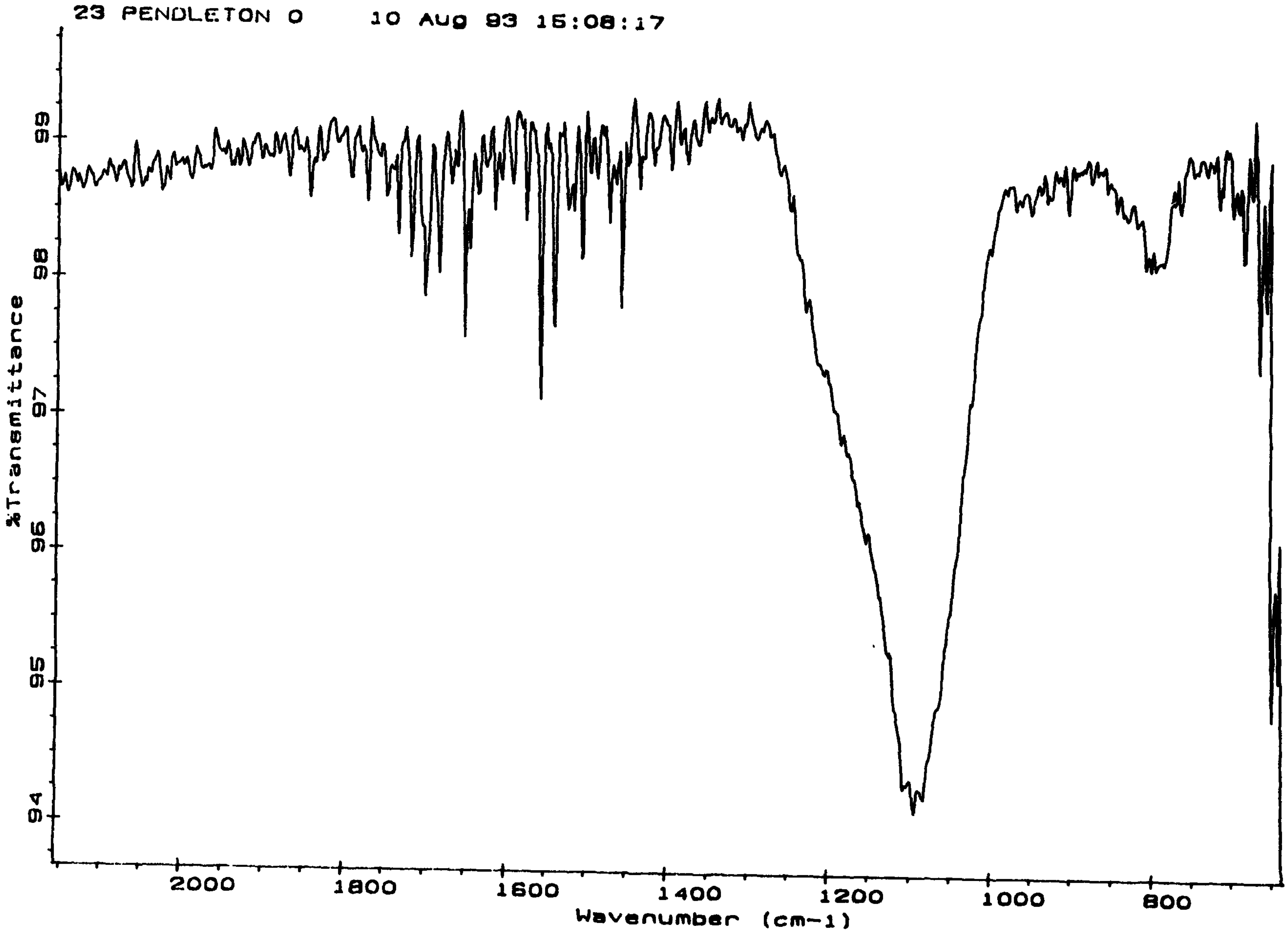

Figure A-15. Camp Pendleton, CA, infrared spectrum

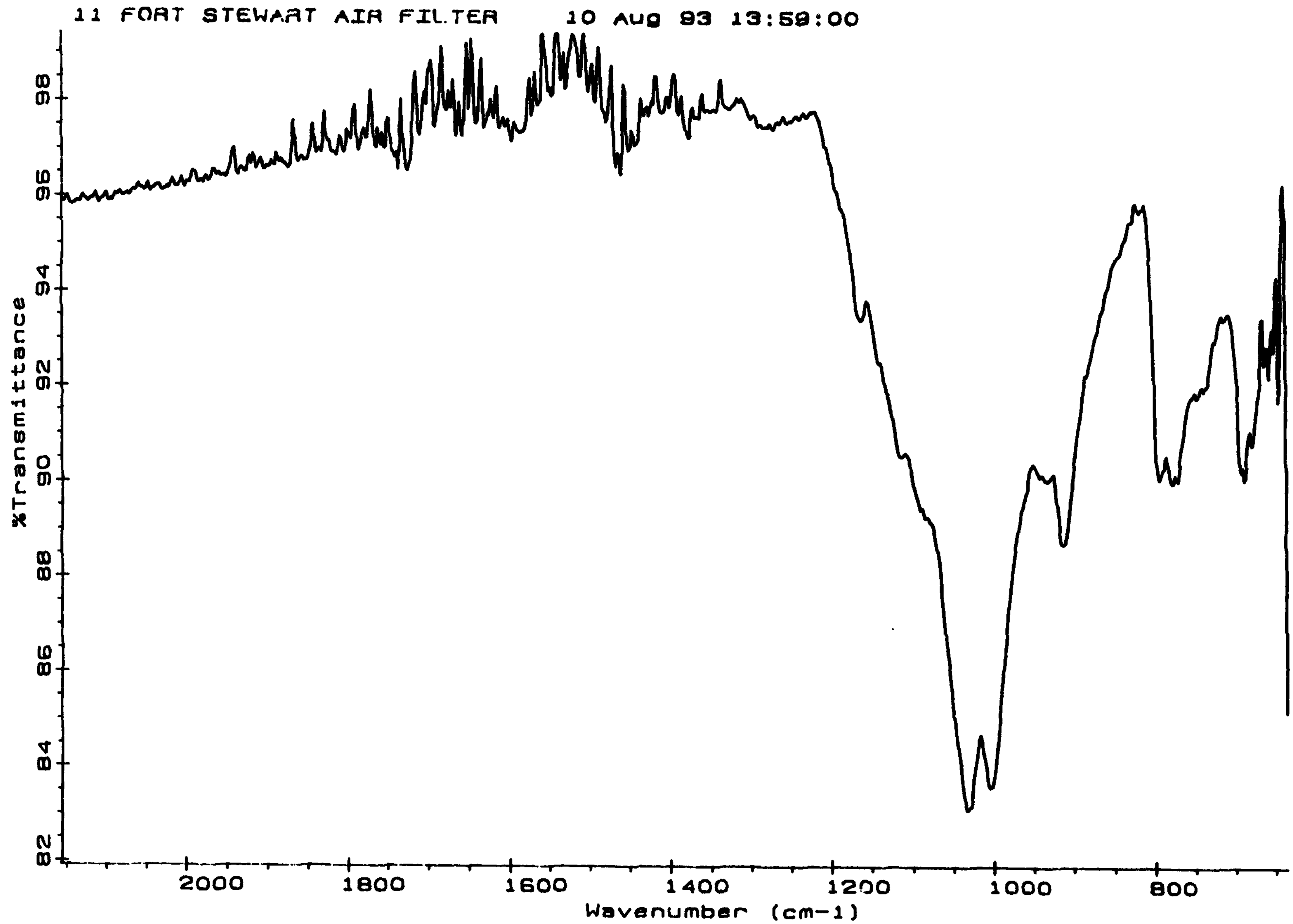

Figure A-16. **Ft. Stewart, GA, air filter debris, infrared spectrum**

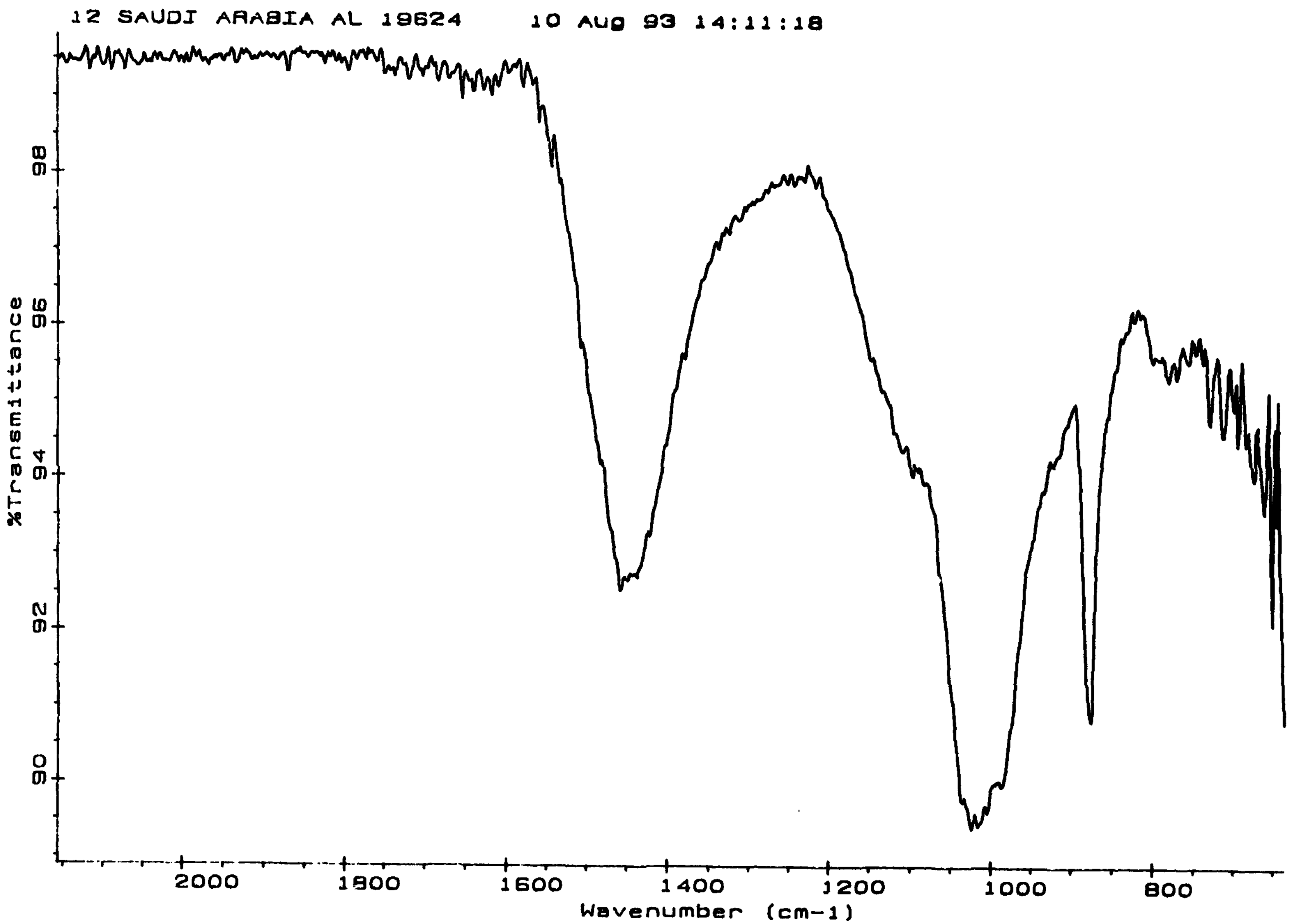

Figure A-17. Saudi Arabia 4 infrared spectrum

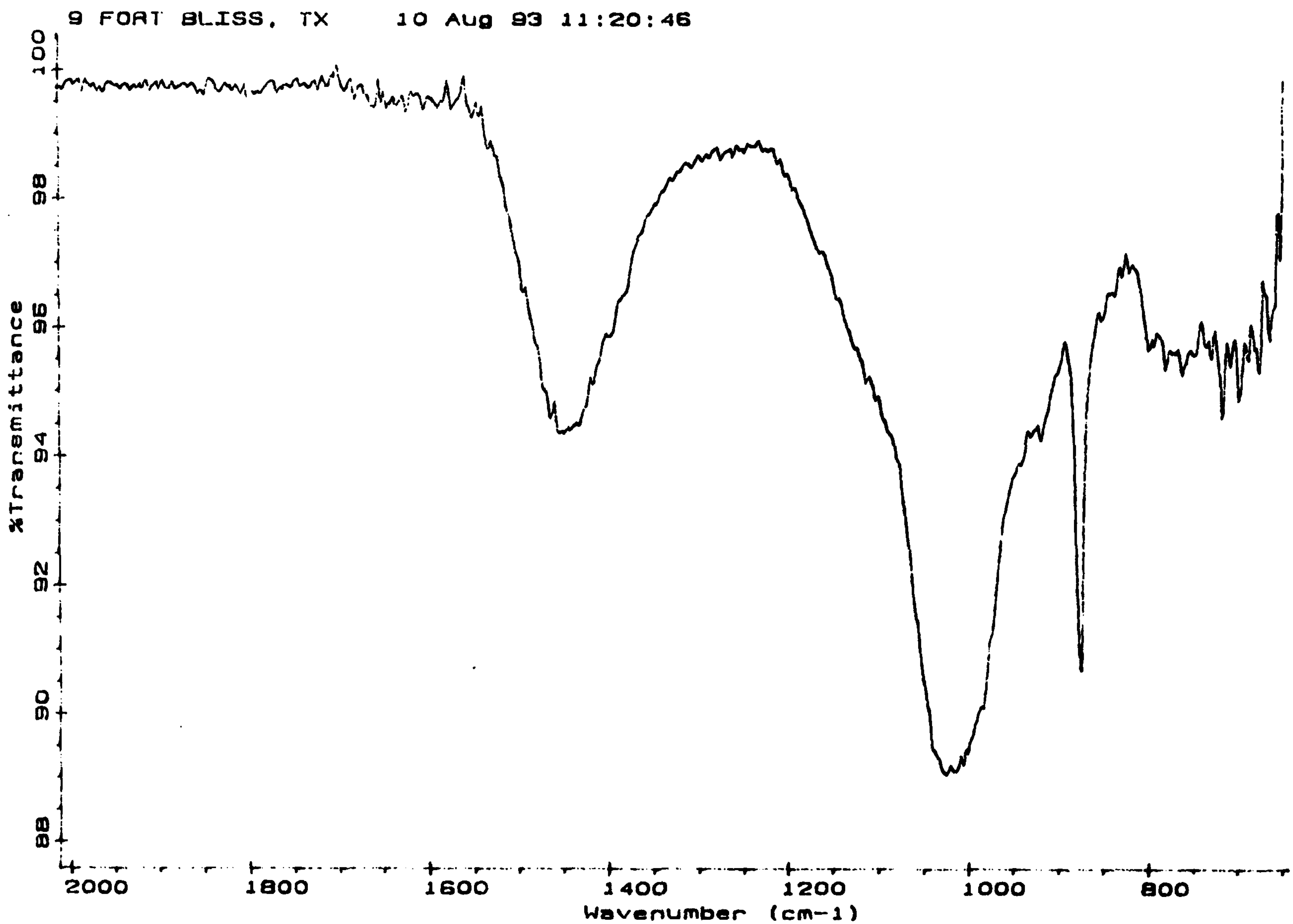

Figure A-18. Ft. Bliss, TX, infrared spectrum

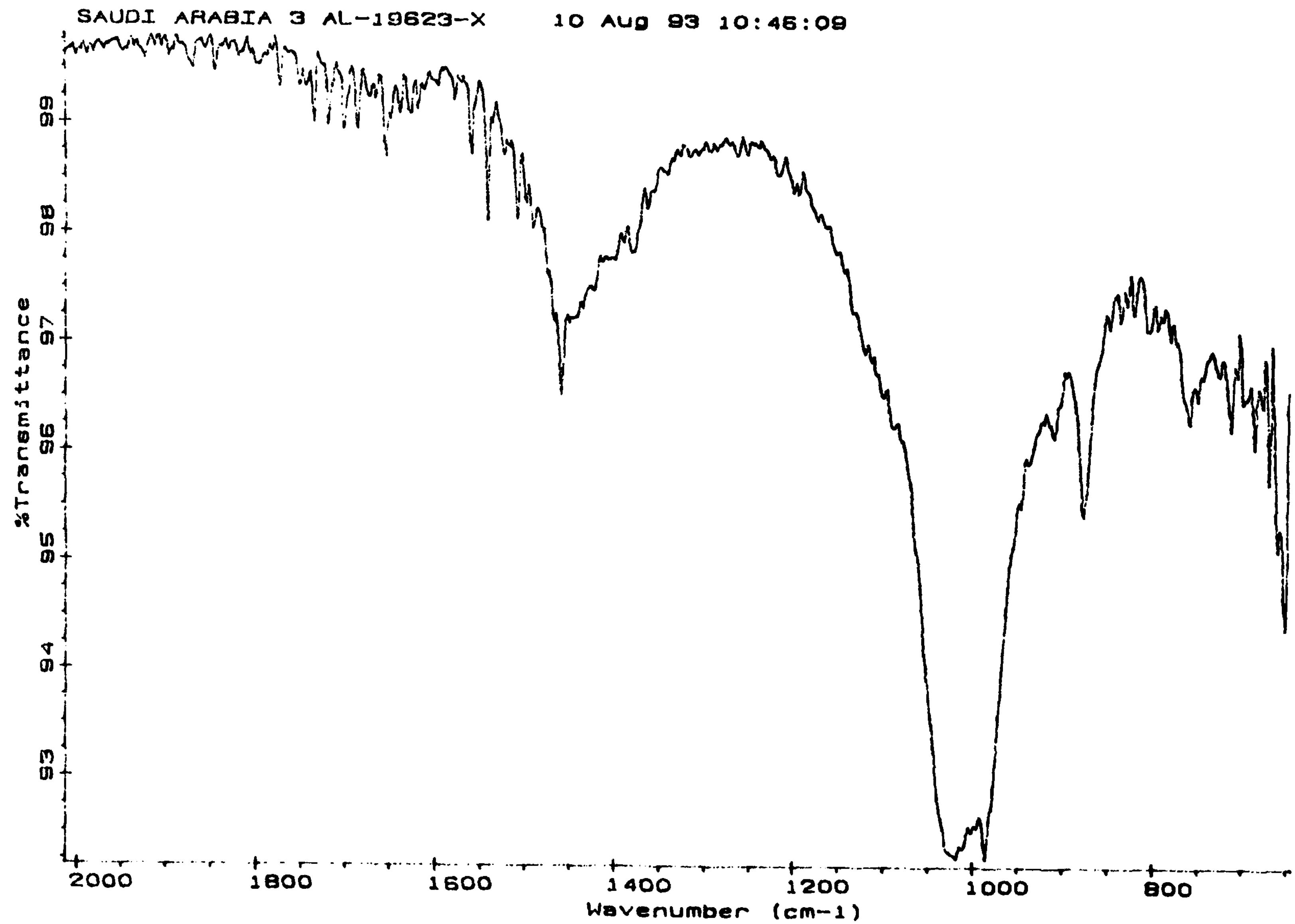

Figure A-19. <u>Saudi Arabia 3 infrared spectrum</u>

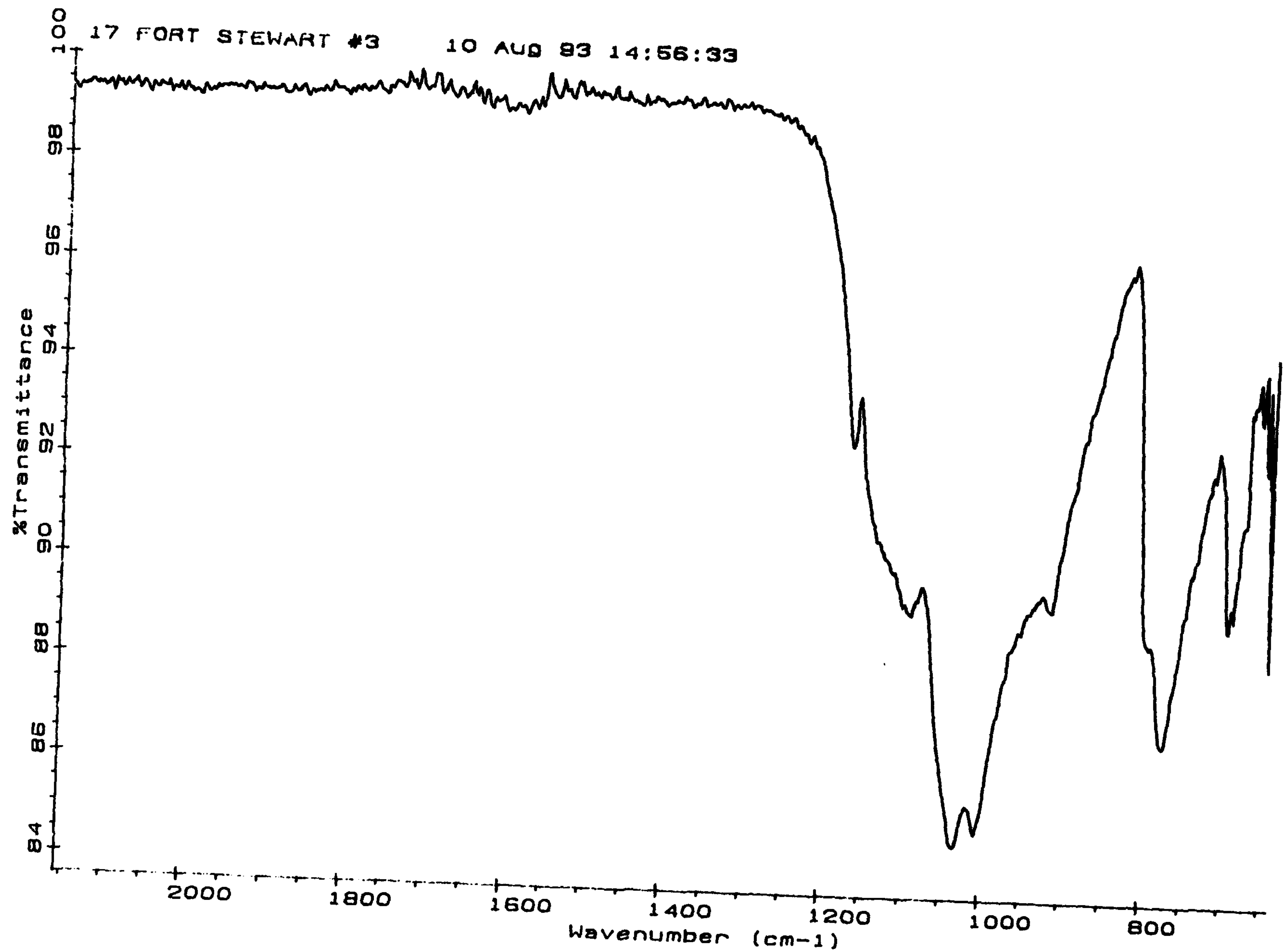

Figure A-20. Ft. Stewart, GA, infrared spectrum

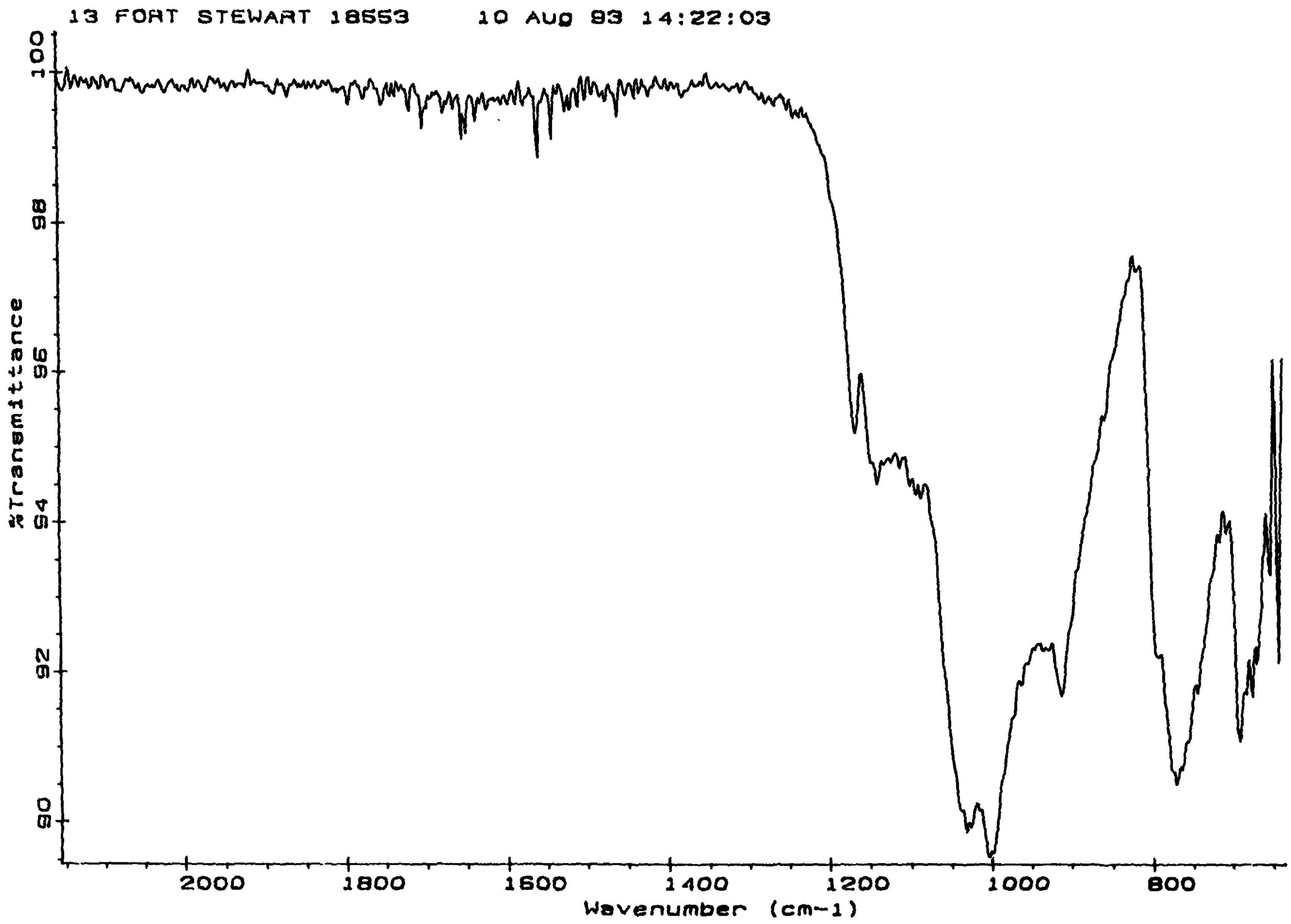

Figure A-21. Ft. Stewart, GA, Range 18553, infrared spectrum

APPENDIX B

Soil Sample SEM Microphotographs

Figure B-1. **Saudi Arabia 1**

Figure B-2. **Saudi Arabia 1**

Figure B-3. Saudi Arabia 2

Figure B-4. Saudi Arabia 5

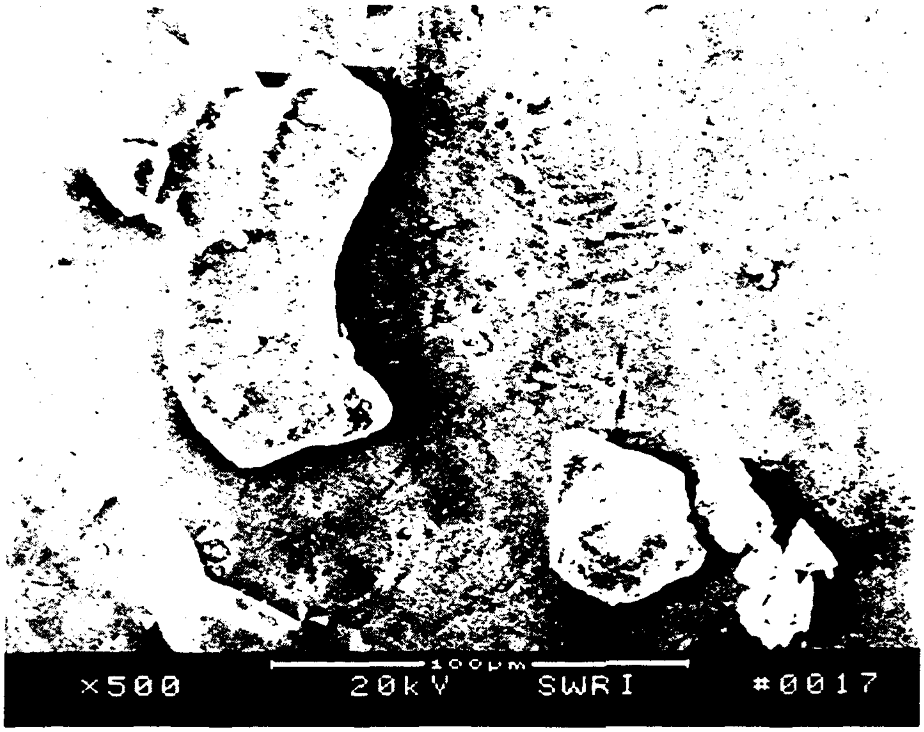

Figure B-5. Fort Irwin, CA (National Training Center)

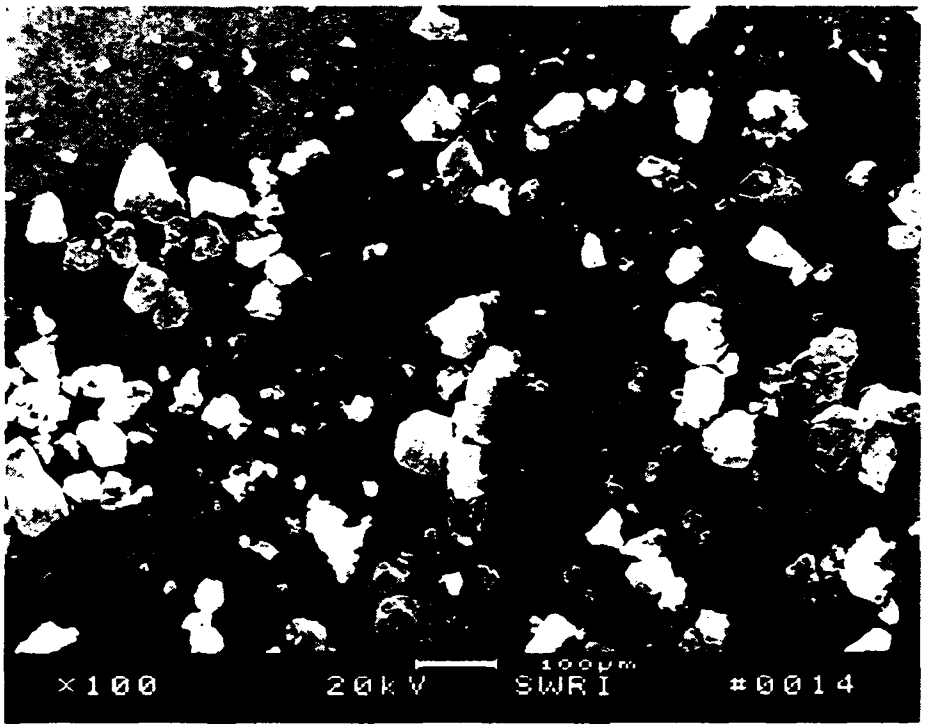

Figure B-6. Fort Stewart, GA

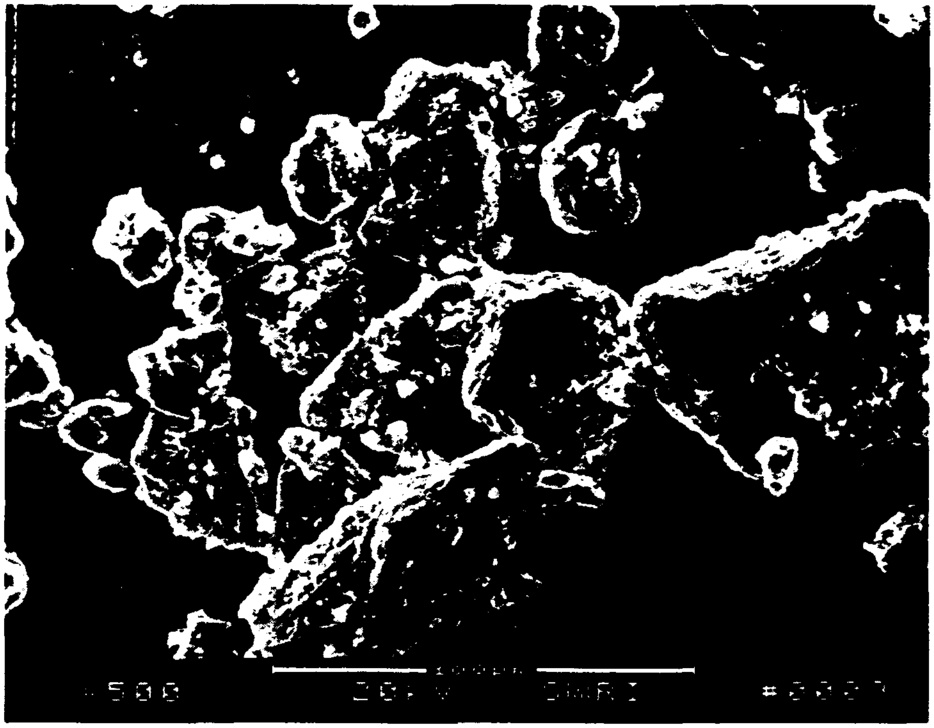

Figure B-7. Fort Stewart, GA, Red Cloud

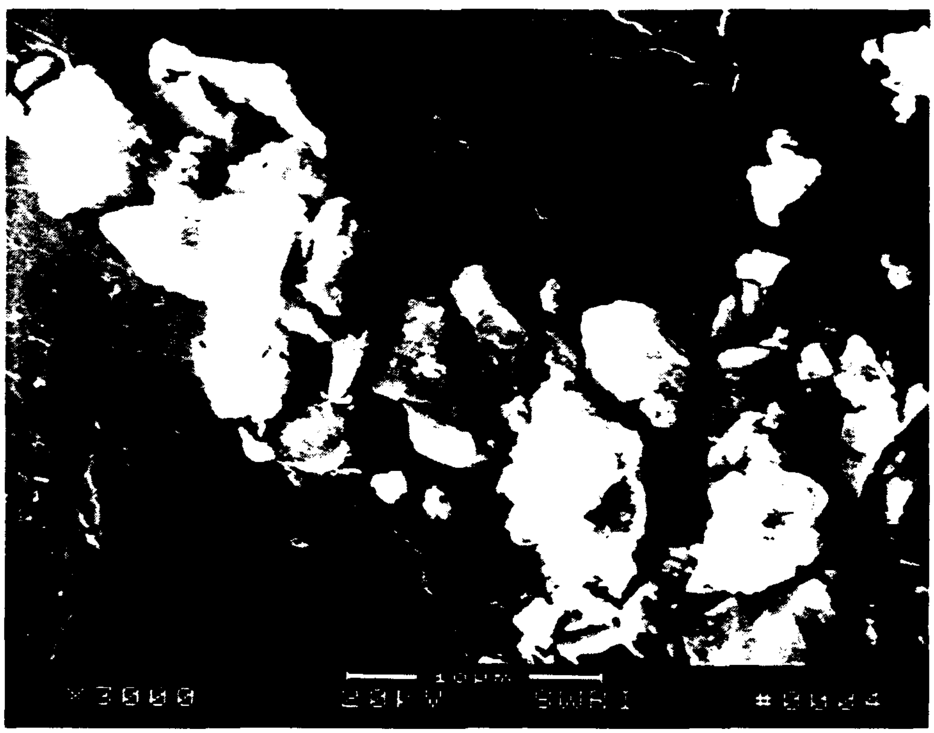

Figure B-8. PTI fine test dust

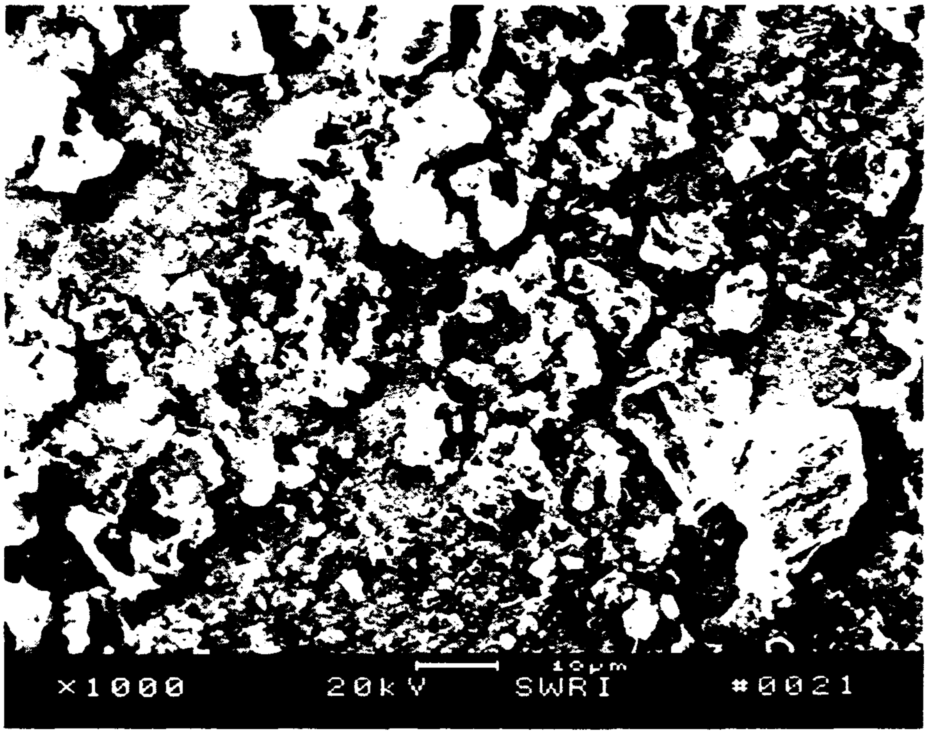

Figure B-9. Twentynine Palms, CA, fuel debris

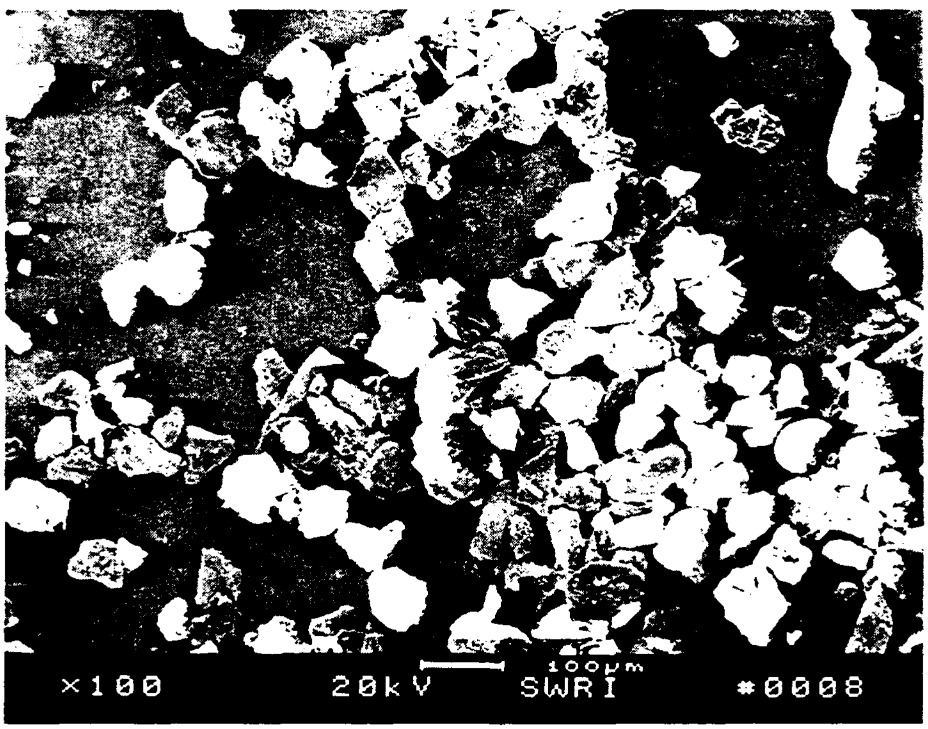

Figure B-10. Camp Pendleton, CA

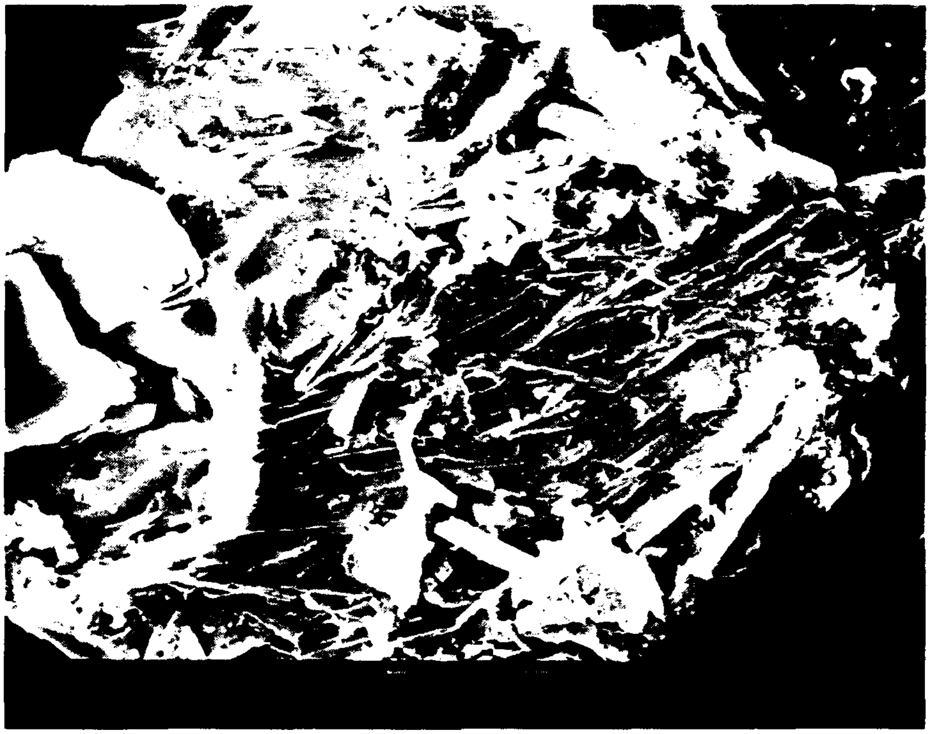

Figure B-11. **Camp Pendleton, CA, airborne dust**

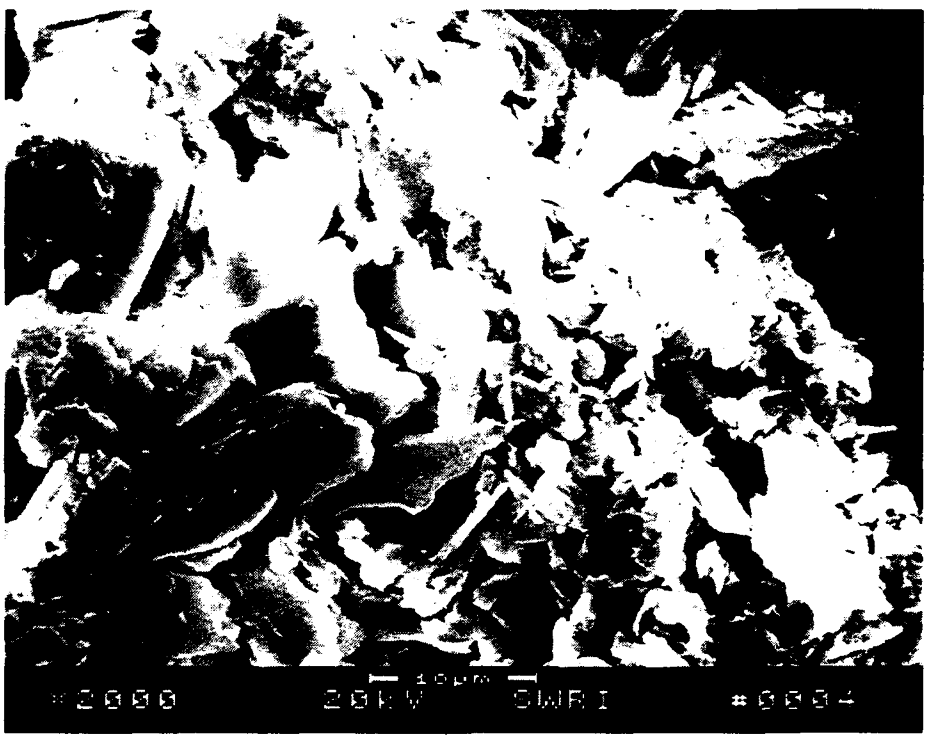

Figure B-12. **Camp Pendleton, CA, airborne dust**

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